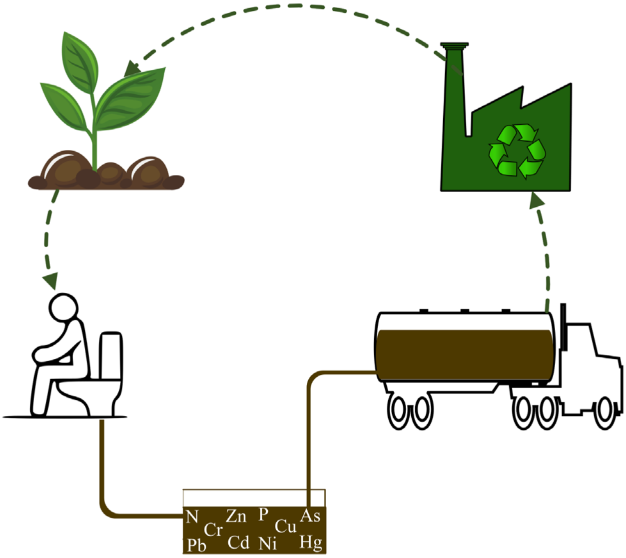
ACTA UNIVERSITATIS AGRICULTURAE SUECIAE

DOCTORAL THESIS NO. 2023:99
FACULTY OF NATURAL RESOURCES AND AGRICULTURAL SCIENCES

Estimating qualities and quantities of faecal sludge to determine resource recovery potential

A case study in Phnom Penh, Cambodia

CHEA ELIYAN



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DOCTORAL THESIS
Uppsala 2023

Acta Universitatis Agriculturae Sueciae
2023:99

Cover: Onsite sanitation system and resource recovery potential
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ISSN 1652-6880
ISBN (print version) 978-91-8046-250-1
ISBN (electronic version) 978-91-8046-251-8
https://doi.org/10.54612/a.57maac58i7

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Print: SLU Grafisk service, Uppsala 2023

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Abstract

A paradigm shift to convert faecal sludge into resources could minimise environmental pollution and public health risks in cities in low- and middle-income countries (LMIC). To support faecal sludge management planning at city scale, this thesis investigated resource recovery potential from faecal sludge, using Phnom Penh as a case and focusing on waterborne systems. Methods used were faecal sludge sampling and analysis, stakeholder interviews, observations and multi-criteria assessment.

Resource recovery potential from faecal sludge in Phnom Penh was found to be limited. Many quality parameters in faecal sludge were low compared with previously reported values, owing to dilution effects of high prevalence of waterborne toilets, addition of water during emptying events, mixed wastewater capture by containment units and connection of containment units to the urban drainage network. Concentrations of two heavy metals (mercury and zinc) exceeded the limits in the Cambodia standard for organic fertiliser and Swedish standard for compost. The highly diluted nutrient content and relatively high heavy metal contamination in faecal sludge limit its reuse potential. However, reuse of sludge could capture around 65 tons of total nitrogen and 13 tons of total phosphorus annually instead of allowing these nutrients to enter natural wetlands.

Three options to tackle the current challenges in faecal sludge management in Phnom Penh were identified: (i) short-term: use of treated faecal sludge as soil conditioner for public green space; (ii) medium-term: upstream source control to prevent contamination of sludge; (iii) long-term: source separation. Solar drying and vermicomposting are appropriate technologies for short-term solutions and co-composting, larval composting and vermicomposting for medium-term solutions, after implementing upstream source controls. For long-term solutions, extensive research on appropriate technologies is needed. Overall, the best option will depend on relative weighs of sustainability criteria and trade-offs for sector stakeholders. These findings can assist sector stakeholders in Phnom Penh and other LMIC cities with similar sanitation systems in improving faecal sludge management.

Keywords: Logistics, LMIC, nutrient recovery, onsite sanitation, physicochemical characteristics, resource-oriented sanitation, sustainability, waterborne system

Utvärdering av kvalitet och kvantitet av slam från enskilda avloppsanläggningar för att bedöma resursåtervinningspotentialen

Sammanfattning

Ett paradigmskifte genom att omvandla avloppsslam från ett avfall till en resurs skulle kunna minimera miljöföroreningar och folkhälsorisker i städer i låg- och medelinkomstländer. Målet med denna avhandling var att stödja planering av slamhantering i stadsskala med fokus på vattenburna avloppssystem. Huvudfokus var att utärdera potentialen för återvinning av resurser från slam där Phnom Penh i Kambodia används som fallstudie. Olika utvärderingsmetoder användes, inklusive provtagning och analys av trekammarbrunsslam från blandade och separerade system med enbart toalettavlopp, intervjuer med intressenter, fältobservationer och multikriterieanalys.

Resursåtervinningspotentialen från slam i Phnom Penh är begränsad. Många kvalitetsparametrar för slam var i det lägre intervallet jämfört med andra tidigare rapporterade värden. Användningen av vattenspolade toaletter, tillsats av vatten under tömning, system som inte separerande olika avloppsvattenfraktioner, och anslutning till stadensavloppsnät bidrar till utspätt slam i Phnom Penh. Två av de studerade tungmetallerna (kvicksilver och zink) hade halter över tillåtna gränser i Kambodjas standard för organisk gödsel såväl som de svenska gränsvärdena för kompost. Det mycket utspädda näringsinnehållet och den relativt höga tungmetallföroreningen i slammet begränsar nuvarande återanvändningspotential. Cirka 65 ton totalkväve, 13 ton totalfosfor kunde årligen samlas in i stället för att släppas ut i våtmarkerna runtom staden.

Tre alternativ föreslås för hantering av dagens utmaningar med slamhantering i Phnom Penh: i) kortsiktig lösning: användning av behandlat slam till jordförbättring för offentliga grönområden; ii) Lösning på medellång sikt: uppströmsarbete för att förhindra kontaminering av slammet med tungmetaller; iii) Lösning på lång sikt: system för källsortering av avloppsfraktioner. För den kortsiktiga lösningen skulle soltorkning och maskkompostering vara lämpliga tekniker. Samkompostering, BSFL-kompostering och maskkompostering är lämpliga tekniker på medellång sikt efter implementering av åtgärder uppströms. En långsiktig lösning med källsortering skulle resultera i högre återvinning av resurser men mer forskning kring lämplig teknik krävs innan fullskalig implementering. Valet av alternativ beror dock på vilka hållbarhetskriterier som bedöms viktigast och vilka avvägningar som valts av intressenterna i sektorn. Resultaten i denna studie ger viktiga input för att vägleda sektorsintressenter i Phnom Penh och andra städer i låg- och medelinkomstländer med jämförbara avloppssystem för korrekt planering av slamhantering.

Keywords: Logistics, LMIC, nutrient recovery, onsite sanitation, physicochemical characteristics, resource-oriented sanitation, sustainability, waterborne system

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. **Eliyan**, C., Vinnerås, B., Zurbrügg, C., Koottatep, T., Sothea, K. & McConville, J. (2022). Factors influencing physicochemical characteristics of faecal sludge in Phnom Penh, Cambodia. *Journal of Water, Sanitation and Hygiene for Development,* 12 (1), 129-140.

II. **Eliyan**, C., McConville, J.R., Zurbrügg, C., Koottatep, T., Sothea, K. & Vinnerås, B. (2022). Generation and management of faecal sludge quantities and potential for resource recovery in Phnom Penh, Cambodia. *Frontiers in Environmental Science,* 10, 869009.

III. **Eliyan**, C., McConville, J., Zurbrügg, C., Koottatep, T., Sothea, K. & Vinnerås, B. (2024). Heavy metal contamination of faecal sludge for agricultural production in Phnom Penh, Cambodia. *Journal of Environmental Management,* 349, 119436.

IV. **Eliyan**, C., McConville, J., Zurbrügg, C., Koottatep, T., Sothea, K. & Vinnerås, B. (2023). Sustainability assessment of faecal sludge treatment technologies for resource recovery in Phnom Penh, Cambodia. *Environmental Technology and Innovation,* 32, 103384.

Papers I-IV are reproduced with the permission of the publishers.

The contribution of Chea Eliyan to the papers included in this thesis was as follows:

I. Planned the study together with BV, JM, CZ and TK. Performed data collection and sample analysis, and carried out data curation with support from KS. Carried out data analysis with inputs from JM and BV. Wrote the paper, with revisions by all co-authors.

II. Planned the study together with BV, JM, CZ and TK. Performed data collection and carried out data computation with support from KS. Carried out data analysis with inputs from JM, BV and KS. Wrote the paper, with revisions by all co-authors.

III. Planned the study together with BV, JM, CZ, TK and KS. Performed data collection, analysed the samples and carried out data computation. Carried out data analysis with inputs from JM and BV. Wrote the paper, with revisions by all co-authors.

IV. Planned the study together with BV, JM, CZ, and TK. Performed data collection and carried out data computation with support from KS. Carried out data analysis with inputs from JM and BV. Wrote the paper, with revisions by all co-authors.

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Abbreviations

As	Arsenic
BOD	Biochemical oxygen demand
BSFL	Black soldier fly larvae
Cd	Cadmium
Cr	Chromium
Cu	Copper
DO	Dissolved oxygen
GHGs	Greenhouse gases
Hg	Mercury
MCA	Multi-criteria assessment
Ni	Nickel
NGO	Non-Governmental Organisation
O & M	Operation and maintenance
Pb	Lead
SDG	Sustainable Development Goal
TN	Total nitrogen
TP	Total phosphorus
TS	Total solids
TSS	Total suspended solids
UDDT	Urine-diverting dry toilet
UDFT	Urine-diverting flush toilet
USEPA	United State Environmental Protection Agency
VS	Volatile solids
VSS	Volatile suspended solids
WHO	World Health Organization
Zn	Zinc

1. Introduction

Progression towards United Nations Sustainable Development Goal (SDG) target 6.2 (Access to adequate and equitable sanitation and hygiene for all by 2030) needs to be accelerated, since otherwise there will likely be 2.8 billion people worldwide without safely managed services (WHO & UNICEF, 2021). Safely managed sanitation is defined as access to improved sanitation facilities that are not shared with others, and where excreta are safely disposed of *in situ* or removed and treated off-site (WHO & UNICEF, 2021). Approximately 1.8 billion people worldwide (63% of studied households in 58 countries across all six WHO regions) rely upon onsite sanitation, with more than 80% of such facilities found in low- and middle-income countries (Berendes *et al.*, 2017). Faecal sludge generated from onsite sanitation is a combination of urine, faeces and other input materials, with or without greywater (Strande *et al.*, 2014). Faecal sludge needs to be safely managed from onsite containment units to final disposal or reuse, but unfortunately a large proportion of faecal sludge is often not properly managed, with lack of sanitary emptying, limited/no treatment plants and indiscriminate disposal (Harada *et al.*, 2016). Therefore, proper faecal sludge management involves addressing the whole sanitation service chain (Boot & Scott, 2008).

Urbanisation and population growth are currently increasing the amounts of faecal sludge generated (Zewde *et al.*, 2021; Singh *et al.*, 2017), while increased piped water coverage and capacity to provide greater water volumes to households will likely result in even larger volumes of wastewater and faecal sludge in future (Berendes *et al.*, 2017). Faecal sludge often ends up in the open environment (PPCA, 2021; Hafford *et al.*, 2018), leading to disease transmission, environmental pollution and loss of aesthetic quality in the environment (Graham & Polizzotto, 2013; Kuffour *et al.*, 2013). The service coverage for faecal sludge collection and treatment facilities in most low- and middle-income nations is insufficient (Taweesan *et al.*, 2017). In fact, appropriate faecal sludge collection and transportation is one of the major challenges facing these countries (Chandana & Rao, 2021b), together with proper faecal sludge management (Berendes *et al.*, 2017).

Viewing human waste as a potential resource could be part of a paradigm shift toward sustainable sanitation and faecal sludge management (Andersson *et al.*, 2016). Different types of resources could be recovered from faecal sludge, such as fertiliser, fuel, soil conditioner, building material, protein, animal feed and water for irrigation (Andriessen *et al.*, 2019). The use of human faeces for crop production in agriculture was once traditional practice (Cofie *et al.*, 2016). Nutrient recovery for use in agriculture is now the most common form of faecal sludge reuse (Samal *et al.*, 2022). Proper faecal sludge management through recovery of nutrients in low- and middle-income countries could minimise environmental pollution and benefit the agriculture sector. It is argued that these benefits could offset some of the upfront costs of treatment (Zewde *et al.*, 2021; Hafford *et al.*, 2018). High operating costs for urban sanitation have been identified as the major constraint in sustaining service delivery (Manga *et al.*, 2020).

Only small proportions of the resources contained in wastewater and sludge in low- and middle-income countries are recovered in a safe manner (Drechsel *et al.*, 2015; Klingel *et al.*, 2002). Changing this situation will require better treatment options and increased capacity to handle the massive quantities of faecal sludge generated (Michael Steiner *et al.*, 2002). In addition, data on the qualities and quantities of faecal sludge generated will be required for proper faecal sludge management at citywide scale (Krithika *et al.*, 2017; Boot & Scott, 2008). However, accurate estimation of the qualities and quantities of faecal sludge at citywide scale is complicated and such data are often lacking (Chandana & Rao, 2022; Strande *et al.*, 2018; Krithika *et al.*, 2017) or derive from desk-based studies (Peal *et al.*, 2015). Selection of an appropriate treatment technology is difficult due to the wide range of characteristics of faecal sludge with respect to source, season and locality (Krithika *et al.*, 2017; Appiah-Effah *et al.*, 2014; Bassan *et al.*, 2013b; Dodane *et al.*, 2012). Therefore, reliable estimates of the qualities and quantities of faecal sludge are important inputs when designing a treatment plant with resource recovery, to avoid over- or under-dimensioned infrastructure.

There is a general need to improve current faecal sludge management practices with an initiative for resource recovery in most cities in low- and middle-income countries. The aim in this thesis was therefore to address the challenges in faecal sludge management by producing baseline data on faecal sludge qualities and quantities, logistics and resource recovery potential. Such data are critical inputs for future faecal sludge management planning in cities in low- and middle-income countries.

2. Aims and structure

2.1 Overall aim of the thesis

The overall aim of this thesis was to support faecal sludge management planning at citywide scale, focusing on waterborne systems. The main focus of the analysis was to determine the resource recovery potential of faecal sludge. This was done by determining the qualities and quantities of faecal sludge, identifying challenges in current faecal sludge management practices and considering appropriate treatment technologies, using the city of Phnom Penh, Cambodia, as a case study. The intention was to provide data support for accelerating progression towards safe management of sanitation services in Phnom Penh and other cities with a similar sanitation context. To meet the overall aim of the work, the following research questions were formulated:

- What quality and quantity of faecal sludge are produced at citywide scale?
- What are the main challenges in faecal sludge management at citywide scale, including current general practices, logistics and treatment/disposal?
- What are the opportunities for resource recovery from faecal sludge?
- What sustainable faecal sludge treatment technologies are appropriate for cities in low- and middle-income countries?

These research questions were addressed in Papers I-IV. Specific objectives in the different papers were to:

- Provide baseline data on physicochemical qualities and quantities of faecal sludge generated in household onsite sanitation units in Phnom Penh (Papers I & II)

- Determine whether faecal sludge qualities are related to variations in demographic and technical conditions of the containment units (Paper I)
- Identify current faecal sludge management practices, logistics and material flow pathways in Phnom Penh (Paper II)
- Quantitatively estimate the content of nutrient resources (nitrogen and phosphorus) in faecal sludge (Paper II)
- Determine the concentration of heavy metals in raw faecal sludge collected from household and restaurant sources in Phnom Penh, and assess the suitability of faecal sludge for agricultural reuse (Paper III)
- Identify appropriate faecal sludge treatments with resource recovery potential alternatives to incentivise and support sanitation stakeholders in faecal sludge management in low- and middle-income countries (Paper IV).

2.2 Structure of the thesis

This thesis is based on the studies described in Papers I-IV, which build on each other as indicated in Figure 1. The studies covered the entire sanitation service chain, starting from characterising the physicochemical qualities of faecal sludge from household onsite containment units (Paper I) and quantifying faecal sludge generated at household level (Paper II), identifying current faecal sludge management practices and the final fate of collected faecal sludge and its nutrient content, and estimating the potential for recovery of nutrient resources (nitrogen, phosphorus) (Paper II). After these baseline data had been collected, the concentrations of heavy metals in faecal sludge deposited at two main disposal sites identified in Paper II were determined and the suitability of faecal sludge for agricultural reuse was assessed (Paper III). Based on the results, some conclusions were drawn regarding risks of more circular sanitation systems for faecal sludge. Sustainable solutions to treat faecal sludge for pollution prevention and to avoid the heavy load of pollutants to wetland systems, while at the same time recovering the nutrient content, were assessed in Paper IV. The intention was to support sanitation planners in cities in low- and middle-income settings in their decision-making on faecal sludge management, in order to accelerate safe management of sanitation service in such cities.

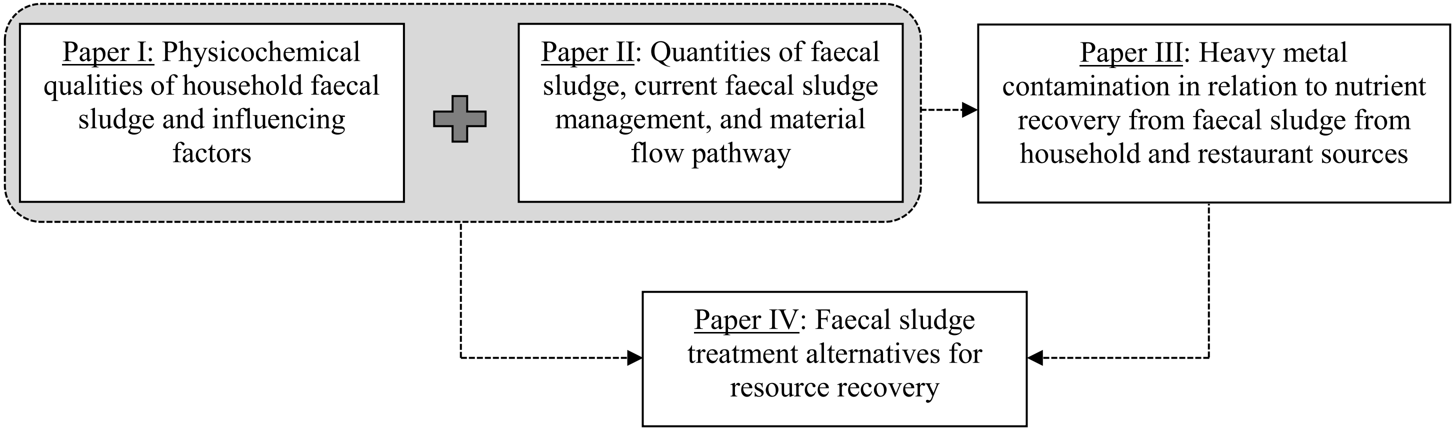

Figure 1. Structure of the research on faecal sludge management in this thesis. Paper I provided baseline data on physicochemical characteristics and various factors influencing these characteristics. Paper II estimated faecal sludge quantities and pathways, and resource content. Paper III assessed the risks associated with more circular sanitation systems. Paper IV considered faecal sludge treatment alternatives to enable resource recovery.

3. Background

3.1 Faecal sludge management coverage, issues and challenges

Faecal sludge generated from onsite sanitation is a combination of urine, faeces and other input materials, with or without greywater (Strande *et al.*, 2014). The input materials can be flush water, anal cleansing water, anal cleansing materials and solid waste, depending on the habits of users and the type of onsite sanitation technology used (Strande *et al.*, 2020). Onsite sanitation refers to a sanitation system in which excreta and wastewater are collected and stored or treated at the site where they are generated (McConville *et al.*, 2020b; Tilley *et al.*, 2014). Onsite sanitation plays a vital role in increasing sanitation coverage around the globe, since it is a low-cost option compared with sewer-based systems when population density is below 112 individuals per hectare (Manga *et al.*, 2020).

Proper faecal sludge management means that faecal sludge is contained, collected, treated and then safely disposed of or reused (WaterAid, 2019). (Figure 2). Unfortunately, more than half of total population (51%) living in 39 cities in low- and middle-income countries use onsite sanitation and only 31% of these have access to safe management service (Peal *et al.*, 2020), according to 'shit-flow' diagrams visualising how wastewater and excreta flow in a city from generation to final disposal/reuse (www.sfd.susana.org). The key drivers of unsafe management include faecal sludge not contained and not emptied from onsite sanitation systems (14%), faecal sludge emptied but not delivered to treatment plant (18%) and faecal sludge delivered to treatment plant but not treated (3%) (Peal *et al.*, 2020). Such unsafe practices have environmental and public health implications (Kuffour *et al.*, 2013).

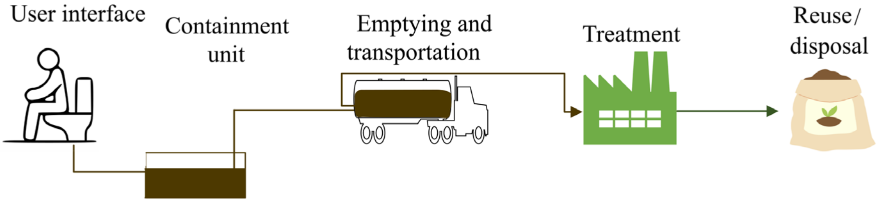

Figure 2. Components of the onsite sanitation service chain: a user interface, an onsite containment system (different types) that normally requires emptying when full or clogged, transportation to a treatment plant and safe reuse/disposal.

In 2020, only 54% of the world's population had access to a safely managed sanitation service (WHO & UNICEF, 2021). This means that to achieve United Nations SDG target 6.2, the current rate of progress needs to be quadrupled. Onsite sanitation is most common sanitation system used by the urban population in Asian countries, where access to safely managed sanitation varies from one country to another (Figure 3). Urban dwellers in Lao People's Democratic Republic and Myanmar have the highest access to safely managed services, while urban dwellers in Cambodia and Vietnam had no access to such services in 2020 (WHO & UNICEF, 2021). Thus efforts are needed to enable Cambodia and Vietnam to catch up with neighbouring countries and make progress towards achieving SDG target 6.2.

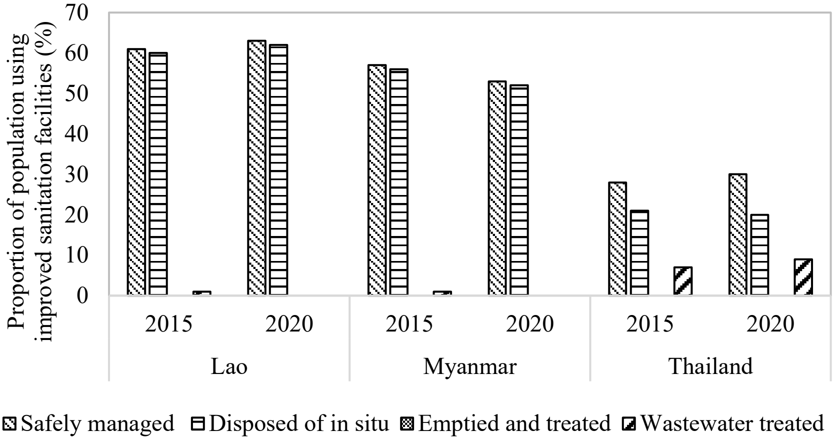

Figure 3. Proportion of the urban population using improved sanitation facilities (excluding shared) in selected Asian countries in 2015 and 2020. Data source: (WHO & UNICEF, 2021)).

3.2 Faecal sludge quantification and characterisation

3.2.1 Faecal sludge quantification

Accurate estimation of the volume of faecal sludge generated is needed for proper planning for faecal sludge management at citywide scale. Sludge volume is an important design input for appropriate dimensioning of the infrastructure required for collection and transportation networks, the area required for a treatment plant, and reuse or disposal options (Wanda *et al.*, 2021; Strande *et al.*, 2014). The volume produced must be estimated based on actual field conditions (Jain *et al.*, 2022) as the quantity of faecal sludge generated varies between cities (UNEP, 2016; Chowdhry & Kone, 2012). However, there are two theoretical methods for quantifying faecal sludge volume, depending on the quantification goal.

Faecal sludge production

Knowledge of faecal sludge production is applicable when the goal is to determine maximum expected sludge load at a treatment plant in a city (Niwagaba *et al.*, 2014). The quantity of faeces and volume of urine produced varies from one location to another, depending on factors such as dietary habits, socio-economic factors, weather and water availability (Polprasert & Koottatep, 2017). For instance, the generation rate in Thailand is 0.6-1.2 L urine/cap/day and 120-400 g wet faeces/cap/day (Schouw *et al.*, 2002). In high-income countries (*e.g.* Sweden), the generation rate is 1.5 L urine/cap/day and 100-200 g wet faeces/cap/day (Vinnerås *et al.*, 2006). The design value for urine and faecal wet weight per person and day is 1.4 L and 128 g, respectively (Rose *et al.*, 2015). In addition to the volume of excreta generated, faecal sludge accumulation rate depends on time, spatial habits, frequency of toilet use, eating and drinking habits, and other fractions deposited in the containment unit (domestic wastewater fractions and solid waste) (Niwagaba *et al.*, 2014). The following data are required to obtain a good estimate of faecal sludge production: number of users, location, type and number of different onsite systems, faecal sludge accumulation rate and population fractions at different socio-economic levels. Data collection is challenging and varies from one city to another, but a household survey should generally be conducted to collect such data (Samal *et al.*, 2022).

Faecal sludge collection

Estimation of faecal sludge collection starts with the amount of faecal sludge collected by emptying and transportation operators, with the current demand for these services used to estimate the volume of faecal sludge collected (Niwagaba *et al.*, 2014). The quantity of faecal sludge collected from onsite sanitation systems depends on various factors such as acceptance and promotion of faecal sludge management, demand for emptying and collection services, and availability of a legal disposal site or receiving treatment plant. Data on volume collected can be obtained through interviews, site visits and reviews of internal records made by faecal sludge collection and transport companies, if available. Illegal collection and disposal should also be taken into account, but it is difficult to quantify the volume of faecal sludge dumped illegally in the open environment. Therefore, when estimating faecal sludge volumes for dimensioning a treatment plant, it is important to include a figure for indiscriminate disposal practices in order to avoid underestimation of the required capacity of the treatment plant (Niwagaba *et al.*, 2014). For more accurate estimation, a flow meter could be installed at the discharge site or treatment plant (Samal *et al.*, 2022).

A mass balance approach could also be used to quantify the load of faecal sludge along the service chain (Strande *et al.*, 2021). There are typically six faecal sludge production stages within the sanitation service chain (Figure 4). Stage one is production of excreta (combined urine and faeces production by all users) and stage two is faecal sludge (sum of excreta production and other material) entering the containment unit (Strande *et al.*, 2021). Stage three is accumulation rate of faecal sludge inside the containment unit, which is challenging to estimate with accuracy as it depends on different biological, physical and chemical factors, resulting in high variability in accumulation rate even within a single city (Prasad *et al.*, 2021). For instance, faecal sludge accumulation rate in Kampala, Uganda, is 270-280 L/cap/year (Strande *et al.*, 2018), in Hanoi, Vietnam, it is 30 L/cap/year (Englund *et al.*, 2020) and in 30 cities in Asia and Africa it ranges from 36 to 959 L/cap/year (Chowdhry & Kone, 2012). Accurate prediction of the accumulation rate should take into account containment unit type and water connection (Andriessen *et al.*, 2023). Stage four is faecal sludge emptied but not collected, which is difficult to quantify as such emptying is illegal. Quantification of faecal sludge in this stage can be attempted through site observations, interviews with pit emptying operators and households. Stage five is faecal sludge collected but not delivered to the treatment plant, but illegally discharged. This happens in most low- and middle-income countries where there is no treatment plant or designated disposal site. Quantification of faecal sludge in this step is useful for improving the current situation regarding faecal sludge management in a city. Stage six is faecal sludge collected and delivered to the treatment plant, where the volume can be directly estimated based on daily operations record. The combined faecal sludge quantity in stages four, five and six is equal to faecal sludge accumulation rate (stage 3) (Strande *et al.*, 2021).

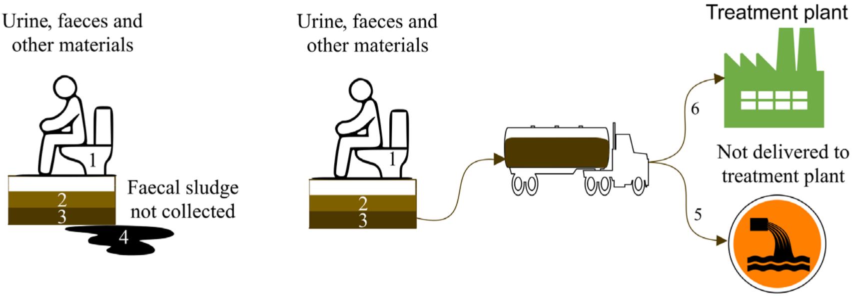

Figure 4. Six stages of faecal sludge production where each stage can be quantified. Stage 1: excreta production, stage 2: faecal sludge production, stage 3: accumulation of faecal sludge, stage 4: faecal sludge emptied but not collected, stage 5: faecal sludge collected but not delivered to treatment plant, stage 6: faecal sludge collected and delivered to treatment plant. Adapted from (Strande *et al.*, 2021; Strande *et al.*, 2018)).

3.2.2 Faecal sludge characterisation

Characterisation of faecal sludge is performed to determine its physical, biological and chemical properties. It is necessary for research, design, implementation and operation of faecal sludge management solutions (Velkushanova & Strande, 2021). Some tools to measure qualities and quantities of faecal sludge are undergoing development, such as the Sludge Snap app, portable penetrometer and Volaser, but validation is still needed. The Sludge Snap app is a simple tool that does not require laboratory analysis and can be used to predict faecal sludge characteristics (Ward *et al.*, 2021). The portable penetrometer measures shear strength profile and depth of pit latrine sludge, metrics which can be used to estimate physical properties of faecal sludge in a pit (Radford & Sugden, 2014). The Volaser device can be used to measure *in situ* volumes of faecal sludge and has been field-tested in seven countries (Andriessen *et al.*, 2023). However, none of these tools is widely available yet.

Key parameters for faecal sludge characterisation include organic matter content, concentrations of solids, nutrients, pathogens and metals, and dewaterability properties. All these parameters are useful for the design of treatment technologies and in planning collection and transportation of faecal sludge (Ward *et al.*, 2019; Gold *et al.*, 2018; Niwagaba *et al.*, 2014). Data on pathogens, degradable organic matter and nutrients are needed for estimating public and environmental health impacts (Strande *et al.*, 2021), and are also useful for quantifying resource recovery potential.

Faecal sludge is highly variable and can be classified based on total solids (TS) concentration into one of four types: liquid faecal sludge (TS >5%), slurry faecal sludge (TS 5-15%), semi-solid faecal sludge (TS 15-25%) and solid faecal sludge (TS>25%). However, faecal sludge cannot be classified in the same way based on other parameters (Velkushanova & Strande, 2021).

Factors that influence the quality of faecal sludge include technical, demographic (cultural/ socioeconomic) and environmental factors (Krueger *et al.*, 2021; Velkushanova & Strande, 2021) (Figure 5). There is no standard range of variation for a particular factor and findings in one study in a specific city cannot be extrapolated to another city in another context (Velkushanova & Strande, 2021). It is therefore important to collect data for specific cities/locations when planning for faecal sludge management and in particular when designing a treatment plant. For example, a treatment plant at Ouagadougou, Burkina Faso, was built based on general characteristics taken from literature data and resulted in twofold overdesigned capacity (Bassan *et al.*, 2013a). Accurate data on faecal sludge characteristics could help avoid over/underestimation of required plant size (Niwagaba *et al.*, 2014).

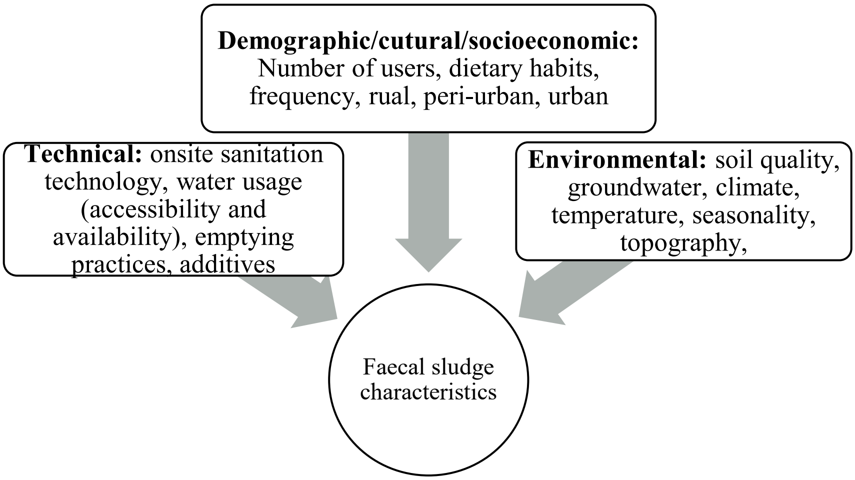

Figure 5. Different technical, environmental and demographic/cultural/socioeconomic factors influencing faecal sludge characteristics in onsite sanitation containment units. Adapted from (Krueger *et al.*, 2021; Velkushanova & Strande, 2021).

In addition to variations in physicochemical quality, heavy metal contamination of faecal sludge is another concern when planning for reuse. A study on faecal sludge characteristics in West Cameroon confirmed that the faecal sludge was suitable for biological treatment, but that this form of treatment was unable to remove heavy metals (Wanda *et al.*, 2021). Heavy metal removal is difficult and costly. Various sources potentially contribute to elevated heavy metal concentrations in faecal sludge. For instance, cadmium (Cd) can enter the sewerage system through stormwater drains and run-off from nearby roads (Agoro *et al.*, 2020), while inappropriate disposal of batteries in onsite sanitation systems can be the source of mercury (Hg) contamination (Strande *et al.*, 2014). For water-based toilet systems, toilet paper and flush water (from a piped water system) can be sources of zinc (Zn), copper (Cu), lead (Pb), Cd and nickel (Ni) (Koch & Rotard, 2001; Storr-Hansen & Rastog, 1988). Faecal excretion contributes less than 10% of the heavy metal load (Koch & Rotard, 2001).

3.3 Treatment technologies

Treatment is required for safe reuse and disposal of faecal sludge. The objective of treatment is to convert unpleasant and harmful material (faecal sludge) into a valuable product that does not pose any risks to the environment or public health (Tayler, 2018). There are numerous treatment technologies available to treat faecal sludge, as illustrated in Figure 6. In general, treatment of faecal sludge consists of two steps: primary and secondary treatment (Singh *et al.*, 2017). Primary treatment is an initial step that aims to separate liquid from solids and the treatment design commonly depends on the solids content in the incoming sludge. Dewatered sludge and supernatant generated in primary treatment require secondary treatment before safe reuse or disposal (Tayler, 2018).

Many treatment technologies are available for solid-liquid separation and each technology has different operational requirements, advantages and disadvantages. Centrifugation has high power cost and is mechanically complex, and thus it is not practical in low- and middle-income countries (Tayler, 2018). Mechanical presses can be used for any solids content (<5% or >5%). The dewatered sludge can be treated based on the specific requirements in the disposal option. Geobags can be used as an aid for dewatering of sludge, but the high cost reduces their feasibility as a dewatering option (Tayler, 2018).

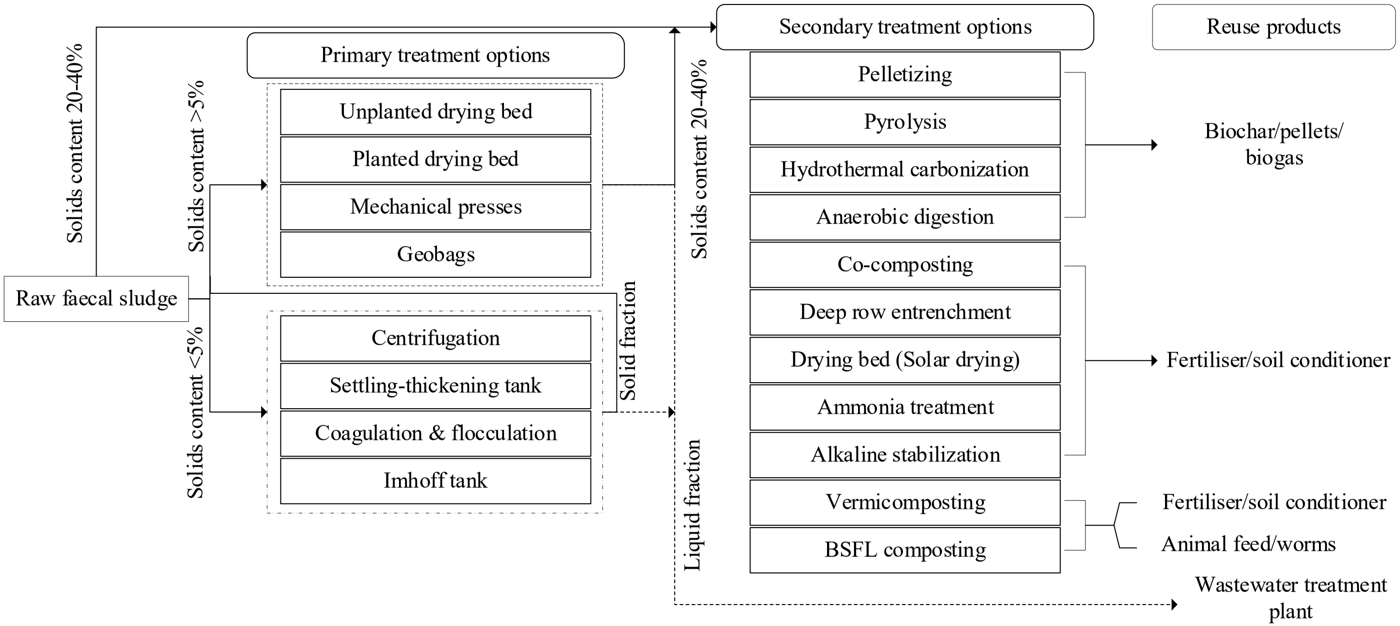

Figure 6. Faecal sludge treatment options. Solids content provides preliminary information for selection of appropriate technologies. Additional inputs might be needed depending on specific technology options selected. Liquid fractions should be sent to a wastewater treatment plant, but those technologies are not listed here. Adapted from Tayler (2018) and Singh *et al.* (2017).

Selection of secondary treatment method depends on the treatment goal. To achieve environmental and public health treatment objectives, faecal sludge needs to be treated in such a way that the pathogen content is significantly reduced, the organic matter and nutrient content is stabilised, and safe reuse of treatment products is possible (Strande *et al.*, 2014). Sludge that is highly contaminated with heavy metals can be used to create products such as bricks (construction material) or energy (pyrolysis, incineration) (Diener *et al.*, 2014). Heavy metals can also be recovered through the microwave digestion method (Afolabi & Sohail, 2017). Recovery of heavy metals can bring both economic and environmental benefits, as it prevents soil and water pollution and avoids risks to human health (Afolabi & Sohail, 2017). The risk posed by heavy metals in faecal sludge should be evaluated on a case-by-case basis.

3.4 Utilisation of faecal sludge

Faecal sludge can be converted to valuable products such as soil conditioner/fertiliser (Figure 7) (Chandana & Rao, 2022), energy (fuel, biogas and hydrothermal carbonisation) (Gold *et al.*, 2017), animal feed/protein production, building material and water for irrigation (Samal *et al.*, 2022). A laboratory-scale study on hydrothermal carbonisation has shown that faecal sludge has an energy content of 19-20 MJ/kg and can produce approximately 2.0 L methane (CH_4) per kg (Fakkaew *et al.*, 2018). The use of faecal sludge as a soil conditioner is generally less profitable compared with other treatment end-uses such as energy production (Diener *et al.*, 2014). However, selection of the most suitable treatment option and preferred treated products depends on the design objectives.

Figure 7. Organic fertiliser produced from co-composting of faecal sludge and organic waste.

The main factors to be considered in selection of technology to generate particular reuse products or product combinations are local context, existing regulations and reuse goals, and relative cost (Strande *et al.*, 2014). Other factors that should be considered are type and quantity of input materials, desired output product, financial resources, local availability of materials, availability of space, soil and groundwater characteristics, availability of a constant source of electricity, skills and capacity, management considerations and local capacity (McConville *et al.*, 2020b).

Market potential for the reuse products from faecal sludge should be taken into account when planning treatment of faecal sludge with resource recovery, as the market varies from city to city and also with local specific context. Market identification would help to ensure that the system is designed for the intended area of application of the reuse products (Diener *et al.*, 2014), which would avoid polluting the environment. When selecting faecal sludge treatment to produce a certain product, market research should be conducted to determine customer/local demand (Schoebitz *et al.*, 2016). To some extent, resource recovery from faecal sludge might not help pay the costs of treatment, but prevents pollution of the environment.

Existing technologies for resource recovery are at different development stages. A few technologies are well-established with scientific evidence, but others are still at the conceptual and innovation stages (Strande *et al.*, 2014). For instance, conversion of faecal sludge into building material needs more scientific evidence, since most of the applications to date have been at local level (Chandana & Rao, 2022). The key selection criteria for treatment technology options are treatment performance, local context, operation and maintenance, and costs (Strande *et al.*, 2014). Those criteria should be taken into account when planning for faecal sludge management.

With regard to health aspects, treated sludge can be used as a soil conditioner/fertiliser, but must fulfil the requirement for biosolids reuse in agriculture in terms of meeting the limits on pathogens and pollutant concentrations established in WHO and USEPA guidelines (WHO, 2006; USEPA, 1994) or other local ordinance. Pathogen inactivation can be achieved in some treatment technologies. For instance, compost from co-composting of faecal sludge and solid waste can be free from pathogens with two months of optimum operation under thermophilic conditions (Strande *et al.*, 2014; WHO, 2006). However, the reuse products from some faecal sludge treatment technologies require further treatment for pathogenic inactivation to meet class A requirements in biosolids standards. These technologies include drying bed (solar drying) (Mathioudakis *et al.*, 2013; Mathioudakis *et al.*, 2009), vermicomposting (McConville *et al.*, 2020b) and black soldier fly larvae (BSFL) composting (McConville *et al.*, 2020b;

Tayler, 2018). While it is important to fulfil the requirement on pathogenic indicators in treatment of reuse products to be used as biosolids, there are also concerns about other chemical pollutants, such as heavy metals, when considering reuse (Manzoor Qadir *et al.*, 2015). To address this concern, a heavy metal indicator is included in the USEPA guidelines on biosolids for land application (USEPA, 1994).

4. Methodology

Different approaches were used for data collection in this thesis. In Papers I-III, the methods used included faecal sludge sampling and analysis, interviews with different stakeholders and field observations (Figure 8). The multi-criteria assessment (MCA) approach was employed in Paper IV to identify the sustainable faecal sludge treatment alternatives. Details of the approaches used for data collection in the different studies are described in this chapter.

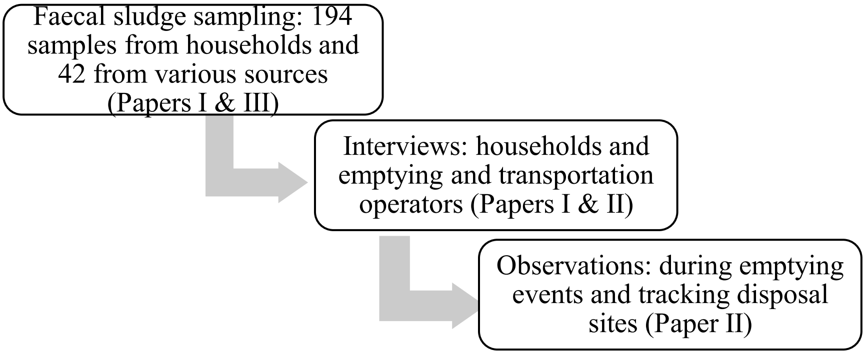

Figure 8. Overview of methodological approaches applied in Papers I-III. Faecal sludge sampling was conducted in two different rounds. Samples taken from household sources were used in Paper I and samples from households and restaurants in Paper III. Interviews with different groups (households and emptying and transportation operators) were conducted during sampling. Observations were performed during emptying and transportation events to identify disposal sites.

4.1 Description of the study area

Phnom Penh is located at around 11°34’N and 104°55’E on the floodplain of the Mekong in Cambodia, above the confluence of the Mekong, Tonle Sap and Bassac rivers. Phnom Penh is divided into 14 districts, five of which are classified as urban and nine as peri-urban, with a total land area of around 679 km^2. With recent urbanisation and development, the total population of Phnom Penh has now reached approximately 2 million people, living in around 500,000 households (NIS, 2020). Phnom Penh has a tropical monsoon climate, with a general temperature range of 30-28°C during the period 2013-2017 (JICA, 2019). There are typically two seasons in Cambodia, a rainy season (June to October) and a dry season (November to May). Mean monthly rainfall data from 2004 to 2013 show that February had the lowest precipitation in that period (8.1 mm) while September had the highest (270 mm), followed by October (240 mm) (JICA, 2016).

Phnom Penh is surrounded by two extensive natural wetlands, Cheung Ek and Kob Srov, which play a key role in natural treatment of wastewater from the whole city before discharging it to final recipient waters. The combined drainage system in the city transports all types of urban wastewater, including stormwater during rainfall events, and offloads it into the natural wetlands (Frenoux *et al.*, 2011). There are 14 pumping stations in Phnom Penh to facilitate transportation of the city's wastewater into the natural wetlands, especially during heavy storm events, to avoid flooding in Phnom Penh. However, the area of these two 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).

Similarly to cities in other low- and middle-income countries, Phnom Penh still has 0% safely managed sanitation (PPCA, 2021; Peal *et al.*, 2015). Onsite sanitation serves the majority (85%) of Phnom Penh residents (PPCA, 2021). Septic tanks and pits are typical onsite sanitation systems used in urban areas of Cambodia (Chowdhry & Kone, 2012). When the tanks are full, clogged or overflowing, local residents often opt for mechanical emptying and transportation services rather than manual emptying. Since piped water supply coverage in the city has now reached 93% (PPCA, 2021), almost all Phnom Penh residents use water-based toilets connected to onsite containment units. These onsite containment units are in turn connected to the urban drainage network if they are located within the coverage areas (Figure 9). There are two types of septic tanks and two types of cesspit commonly in use in Phnom Penh (Paper I), both of which have free flowing supernatant if the containment unit is connected to the urban drainage network.

4.2 Faecal sludge sampling procedures

Sampling of faecal sludge in this thesis was conducted in two different rounds (Papers I-III). In the first sampling round, faecal sludge was collected immediately after emptying events at households, from the discharge valve on the vacuum truck. In the second sampling round, faecal sludge was collected at the two main disposal sites identified in Paper II. Sampling during the second round included faecal sludge from both households and restaurants.

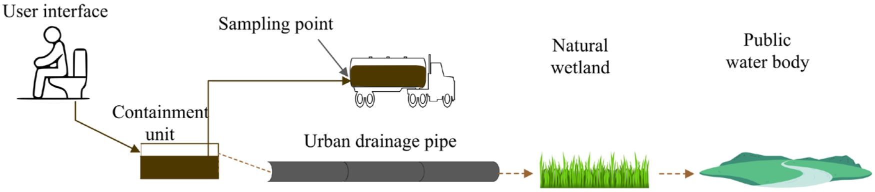

Figure 9. Example of onsite containment unit connected to urban drainage network in Phnom Penh, Cambodia, and faecal sludge sampling point in Paper I.

4.2.1 Household faecal sludge sampling

A preliminary interview with emptying and transportation operators was conducted to obtain their participation in the study. Seven operators agreed to participate and provided information regarding location of households that required their emptying services. A total of 194 faecal sludge samples were collected from the discharge valve of vacuum trucks in the period May to September 2020. To get representative samples based on the population ratio (3:1) in peri-urban and urban areas, a total of 148 samples were collected from peri-urban areas of Phnom Penh, and 46 samples from urban areas (Paper I).

After collection in 500-mL polypropylene bottles, parameters of the samples such conductivity, dissolved oxygen (DO), pH and temperature were measured immediately *in situ*. The samples were then placed in an icebox and transported to the laboratory of the Department of Environmental Science, Royal University of Phnom Penh, for further analysis. Sample handling, preservation and storage for further analysis followed Standard Methods for the Examination of Water and Wastewater (APHA *et al.*, 2017).

4.2.2 Faecal sludge sampling from various sources

In the second sampling round, faecal sludge samples were collected from discharge points in both the rainy (October 2022) and dry seasons (February 2023). A pre-screening step was conducted before taking the samples, where the prerequisites to proceed were source of faecal sludge (from household and/or restaurant) and consent from emptying and transportation operators.

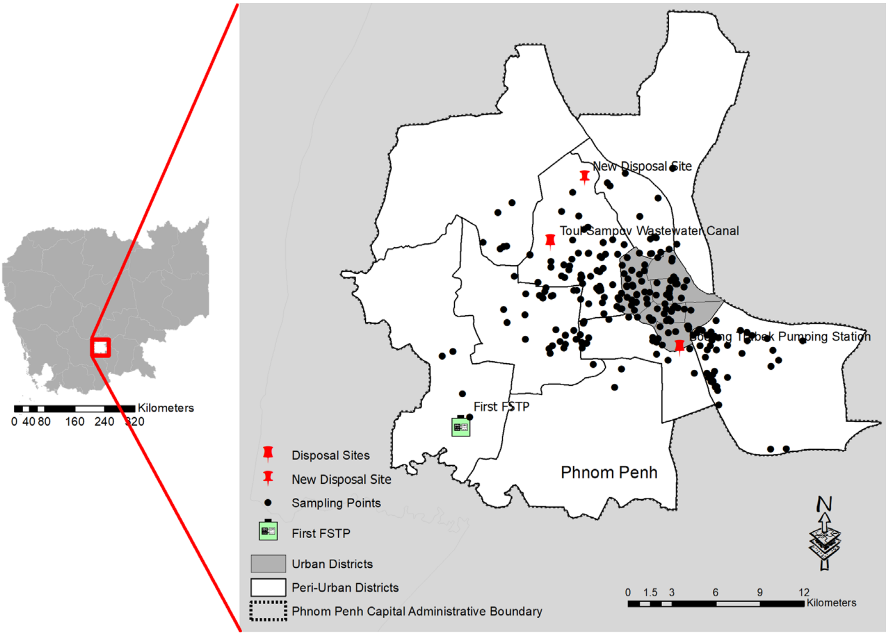

Figure 10. (left) Map of Cambodia showing the location of the study area and (right) map of Phnom Penh showing households where faecal sludge samples were collected and where surveys to collect demographic and technical data were held during sampling (Papers I and II) and the three disposal sites where faecal sludge samples were collected during the rainy and dry seasons (Paper III).

A total of 21 faecal sludge samples were randomly collected at the two main disposal sites, Boeung Trabek pumping station and Toul Sampov wastewater canal, in the rainy season (Figures 10 and 11). Another 21 samples were randomly collected at Boeung Trabek pumping station and at a new disposal site (identified during sampling) in the dry season. The samples taken at the new disposal site replaced samples that were planned to be collected from Toul Sampov wastewater canal (Figures 10 and 11). There was no truck discharge of faecal sludge into Toul Sampov wastewater canal during the sampling campaign, due to stricter monitoring and enforcement by the local authority, and the new disposal site was likely created as a replacement. During rainy season sampling, Beoung Trabek pumping station received more of the faecal sludge generated in the city (>60%) than Toul Sampov canal (Paper II). To obtain representative samples based on discharge ratio, 28 samples were collected at Boeung Trabek pumping station (14 each in the rainy and dry season), seven samples were collected at Toul Sampov canal (rainy season) and seven samples were collected at the new disposal site (dry season) (Paper III).

Figure 11. The three disposal sites used in faecal sludge sample collection for Paper III. (a) Boeung Trabek pumping station, (b) Toul Sampov wastewater canal and (c) new disposal site identified during dry season sampling.

As done during sampling at household sources, measurements of conductivity, DO, pH and temperature were performed immediately *in situ*. These samples were collected in 1000-mL polypropylene bottles, placed in an icebox and transported to the laboratory of the Department of Environmental Science, Royal University of Phnom Penh, for further analysis using standard methods (APHA *et al.*, 2017).

4.3 Stakeholder surveys

After collecting faecal sludge samples (Papers I & II), interviews were conducted with the emptying and transportation operator who provided the service and the household that used the containment unit emptied.

4.3.1 Survey of emptying and transportation operators

The interviews with emptying and transportation operators were conducted in two steps. Initially, a total of 34 emptying and transportation operators were identified as operating mechanical emptying services in the city, and were contacted for interview, using a structured questionnaire. The main purpose of these interviews was to ask for their participation in the faecal sludge sampling campaign. The interviews were conducted via phone, since Covid-19 restrictions meant that the city was locked down. In the second step, the questionnaire was developed and used during interviews with participating operators after collecting faecal sludge samples (Papers I and II). The purpose of these interviews was to gather technical data about the containment system from the emptying and transportation operators and to track the final disposal of emptied sludge from the source households.

4.3.2 Household survey

The purpose of interviewing house owners was to collect relevant data, mainly demographic and technical information, about the containment units and their users, as well as information on practical management of the containment units. These interviews were conducted after collecting faecal sludge samples. The interview 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); containment captures only blackwater (yes or no); number of users (<10, 10-50, >50 people) and containment system age in years since installation (3-10, ≥10-20 and >20 years) (used in Paper I).

Additional information obtained in interviews with households included: demographic information on households, sanitation technology, containment emptying practices, and their opinion concerning improvement of faecal sludge management (used in Paper II).

4.4 Field observations

Field observations were made using a checklist (see Supplementary Information to Paper II). Observations were used to gather information that could only be obtained accurately through direct observation, *e.g.* on safety practices during emptying events and at faecal sludge disposal sites (Paper II). To identify the final disposal site for each extraction from households, permission was requested from the truck driver to accompany the truck to the disposal site. A specific name was assigned to the site at which sludge was discharged and geo-coordinates were recorded using a global positioning device (Garmin GPSMAP 60CSx). Some sludge disposal sites were recorded as unknown, since the truck driver refused permission to accompany the truck to the disposal sites in some cases. Those truck drivers might have wanted to protect their business by concealing sites where they might have dumped faecal sludge illegally. A study of 12 cities in Asia, including Phnom Penh, found that pit emptying operators sometimes dumped sludge illegally (Peal *et al.*, 2015). A recent study also reported indiscriminate disposal of faecal sludge in Phnom Penh (PPCA, 2021).

4.5 Faecal sludge analytical methods

In addition to parameters measured *in situ* at sampling, other parameters of concern in this thesis were: total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS), biochemical oxygen demand (BOD), phosphate-phosphorus (PO_4-P), ammonium nitrogen (NH_4-N) and total phosphorus (TP) (Paper I). Analysis of those parameters followed standard methods for water and wastewater analysis (APHA *et al.*, 2017). Ionic chromatography was used for phosphate analysis. Hach Lange standard tests were used to analyse TP and NH_4-N, following the manufacturer's instructions (APHA *et al.*, 2017; Bassan *et al.*, 2016). Merck test kits were used for nutrient analysis, including PO_4-P, NH_4-N, TP and total nitrogen (TN) (Paper III).

Heavy metals analysed in samples were: arsenic (As), Cd, chromium (Cr), Cu, Hg, Ni, Pb and Zn. The samples were oven-dried at 103-105 °C until constant weight was achieved, and then sent to Bureau Veritas (Cambodia) Limited Laboratory for further analysis (Paper III). Analysis of all heavy metals followed United States Environmental Protection Agency guidelines for biosolids (USEPA, 1996).

4.6 Multi-criteria assessment

A four-step structured approach (Figure 12) was used to identify faecal sludge treatment technologies that can be feasible for faecal sludge generated in urban areas in low- and middle-income settings, using Phnom Penh as a case study (Paper IV). The first step was identification of available options using published literature (McConville *et al.*, 2020a; Tayler, 2018; Singh *et al.*, 2017). In step 2, a list was developed by differentiating primary and secondary treatments to facilitate the subsequent step in the local context (narrowing possible options). The purpose of this was to narrow down the large number of technologies listed in step 1 to a few technologies for use in multi-criteria assessment (MCA). The criteria applied in screening of primary treatment technologies were: 1) use of chemicals; 2) energy requirement; and 3) process complexity. In screening of secondary treatment technologies, reuse potential was included in addition to these three criteria. Technologies that did not meet any one of the criteria were excluded from the MCA step.

In step 3 (MCA), sustainability criteria were selected based on (Andersson *et al.*, 2016) and on criteria used to support decision making on nutrient recovery from faecal sludge in Uganda (McConville *et al.*, 2020a). These criteria were applied to the narrow list of secondary treatment technologies that emerged from the screening in step 2. Four key sustainability areas (health, environment, economic, socio-technical) were considered in the assessment. Different approaches were applied in scoring sub-indicators in the MCA step, such as literature reviews, online survey and stakeholder interviews. In step 4 (stakeholder discussions and ranking), stakeholder input was used in weighing the MCA criteria, based on their judgement on which criteria were most important (total score of 100%). Stakeholders in this step included officers in the sanitation sector in public, non-governmental organisation and development partners. A final ranking of the technologies was drawn up based on the MCA criteria scoring and stakeholder weighting of the criteria during the interview. Scoring was normalised following (Katukiza *et al.*, 2010).

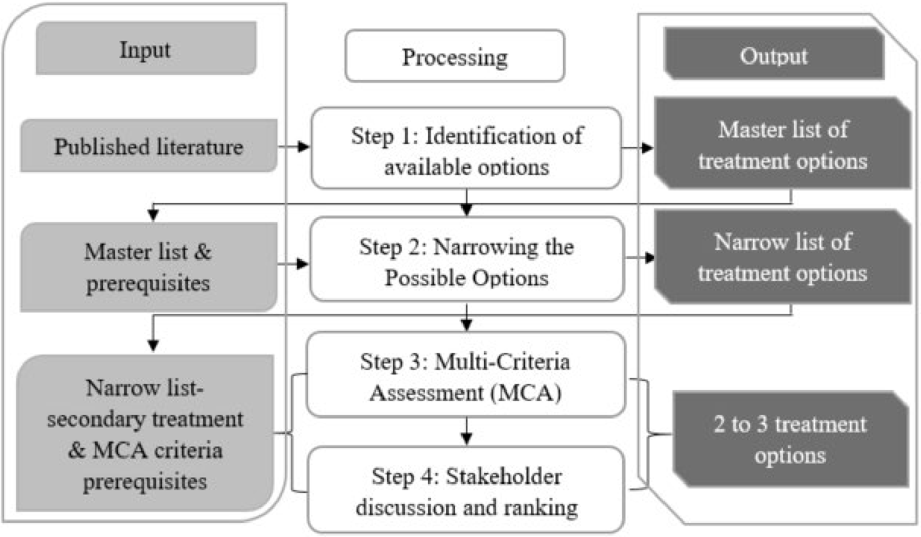

Figure 12. Steps in the multi-criteria assessment (MCA) approach used to identify suitable faecal sludge treatment technologies. Boxes on the left show inputs to each process step (1-4), while boxes on the right show the output from each step.

4.7 Data analysis

4.7.1 Statistical analysis

Microsoft Excel 2010 and R software version 4.0.4 were used to handle the data and conduct the analysis (R Core Team, 2021). Proportion and chi-square test/Fisher's exact tests (for small samples size) were used to assess the different socio-economic characteristics and sanitation management practices of the respondents, based on geographical location of households (peri-urban and urban settings) (Paper II). Descriptive statistics were used to assess physicochemical characteristics and heavy metal concentrations in faecal sludge (Papers I and II).

Data on faecal sludge qualities were log-transformed to achieve normal distribution of the residuals (Paper I). Hypothesis testing on the eight chemical parameters (TS, VS, TSS, VSS, BOD, PO_4-P, TP, NH_4-N) was conducted using the containment unit data collected from household questionnaires and the checklist followed with emptying and transport operators (categorical explanatory variables). A general linear model (lm model in R) was used to assess differences in faecal sludge characteristics between all categorical explanatory variables, in order to identify variables with the greatest influence on each chemical characteristic.

Two-sample t-test and the non-parametric method were used to assess the statistical significance of differences between the rainy and dry season across all parameters studied (Paper III). In all cases (Papers I-III), p-values <0.05 were considered statistically significant.

4.7.2 Spatial analysis of faecal sludge disposal sites

Spatial analysis of faecal sludge disposal sites was performed through linear distance calculation between household (geo-coordinates of original distance) and final site where the extracted sludge was disposed of (geo-coordinates of disposal site), using ArcMap 10.8. Travel distance was classified into three zones around the two main disposal sites (zone I: 0-4 km, zone II: >4-9 km and zone III: > 9-14km). These three zones were classified based on the average and maximum travel distances between source households and the two main disposal sites (Paper II).

4.7.3 Faecal sludge quantification

Quantification of faecal sludge followed the collection method developed by Strande *et al.* (2014) and included the six stages of the sanitation service chain as simplified by Strande *et al.* (2018). The six quantity parameters within the sanitation service chain were: faecal excreta generation rate (Q_1), faecal sludge generation rate (Q_2), faecal sludge accumulation rate (Q_3), amount of faecal sludge emptied (Q_4), faecal sludge collected and delivered to Boeung Trabek pumping station (Q_5), and faecal sludge collected and delivered to Toul Sampov open canal (Kob Srov wetland) (Q_6) (Paper II):

$$Q_1\ (\text{L/year}) = P_{(\text{served})} \times (Q_{(\text{urine})} + Q_{(\text{faeces})}) \qquad (1)$$

where $P_{(\text{served})}$ is population of Phnom Penh in 2020 (2,281,951 (NIS, 2020), $Q_{(\text{urine})}$ is 1.42 L/cap/day (Rose *et al.*, 2015) and $Q_{(\text{faeces})}$ is 0.236 L/cap/day (Strande *et al.*, 2018).

$$Q_2\ (\text{L/year}) = Q_1 + \text{Total containment inflow}_{(\text{septic tank+pit latrine})} \ (2)$$

$$\text{Total containment inflow}_{\text{(septic tank+pit latrine)}} = P_{\text{(served)}} \times C_w \qquad (3)$$

where C_w is water inflow to the containment, with the key assumption that water inflow is the same for all types of containment unit, since containment type does not influence faecal sludge characteristics according to findings in Paper I and water and excreta are only substances entering the containment units. The amount of water entering containment units in developing countries is 58.6 L/cap/day (Koppelaar *et al.*, 2018).

$$Q_3\ \text{(L/cap/year)} = \frac{\text{Emptied volume}}{\text{Number of usersxEmptying frequency}} \qquad (4)$$

Faecal sludge accumulation rate (Q_4) was assumed to be equal to faecal sludge emptied, covering only mechanical operators. Faecal sludge collected and delivered to Cheung Ek wetland (Q_5) or Kob Srov wetland (Q_6) was calculated based on data collected during site observations in disposal site tracking (Paper II).

4.7.4 Resource quantification

The nutrient resources quantified were nitrogen and phosphorus (Paper II). Determination of these was based on Food and Agriculture Organisation, FAO (2019) and followed equations (5) and (6) (Jönsson *et al.*, 2004):

$$\text{Content of N} = 0.13 \times \text{Total food protein} \qquad (5)$$

$$\text{Content of P} = 0.011 \times (\text{Total food protein} + \text{vegetable food protein}) \qquad (6)$$

where total food protein was assumed to be 65.53 g/cap/day and vegetable protein to be 46.8 g/cap/day.

The population fraction used for this calculation was 306,238, representing 22% of households with experience of emptying their containment unit (Frenoux *et al.*, 2011)

Nutrient content in faecal sludge was calculated based on the median concentration of TP and TN in faecal sludge determined in Paper I and III, respectively.

5. Results

5.1 Onsite sanitation management in Phnom Penh

Sanitation in Phnom Penh was found to be dominated by two types of onsite system, cesspit and septic tank, where cesspit served up to 93% of households surveyed (Table 1). Factors influencing sanitation management depending on geographical location (urban or peri-urban) included connection to urban drainage network, toilet type, watertight containment unit, age of toilet/containment, and reason for emptying. Most (95%) of those living within central city areas, but only 65% of those living in peri-urban areas, had their containment unit connected to the urban drainage network ($p<0.001$). Cistern and pour flush toilets were typical types of toilet, where cistern flush toilets were used by more households in urban areas (55%) and pour flush toilets were more popular (45%) in peri-urban settings. Peri-urban areas of Phnom Penh are expanding rapidly outwards, with 47% of households surveyed reporting that their house and their toilet/containment unit were built in the previous 3-10 years. In contrast, around 65% of households/containments located in urban area were older than 10 years. Since most households in urban areas had their containment units connected to the urban drainage network, their units were rarely full as the supernatant flowed freely to the drainage network. In most cases, emptying events for those households were needed due to clogging issues. However, the most common reason for emptying peri-urban households' containment units was that they were full. Regardless of whether the household was located in an urban or peri-urban area, the type of wastewater received by the unit (only blackwater or mixture of other type of wastewater fractions) did not differ significantly (Paper II).

Table 1. *Sanitation management practices employed by responding households in peri-urban and urban areas of Phnom Penh. Values in brackets are percentage of 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				
Cistern flush	94 (48.2)	66 (45.9)	28 (54.9)	0.341
Pour flush	77 (39.5)	65 (45.1)	12 (23.5)	**0.010**
Both	24 (12.3)	13 (9.0)	11 (21.6)	**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 (year)				
<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**

5.2 Qualities of faecal sludge

The physicochemical qualities and heavy metal concentrations in faecal sludge are shown in Tables 2-4. The nutrient content in faecal sludge collected at source from households (Paper I) was analysed to determine the resource recovery potential and to design the best way to capture plant nutrients. The heavy metal and nutrient content in faecal sludge samples collected at disposal sites (Paper III) was analysed to identify the suitability of the faecal sludge for use as biosolids. Sources of variation in faecal sludge physicochemical qualities and seasonal variation in heavy metal content were also assessed.

5.2.1 Physicochemical qualities

The majority of faecal sludge collected was from household sources (93%), rather than restaurant sources (7%) (Paper III). Statistically, data on physical qualities of faecal sludge (conductivity, DO, pH, and temperature) (Tables 2 and 3) were normally distributed (Papers I and III). Physical qualities of faecal sludge from all sources fell within similar ranges.

Table 2. *Summary statistics on faecal sludge parameters for all samples collected from household sources. SD = standard deviation (n=194), DO = dissolved oxygen, BOD = biological oxygen demand, TS = total solids, VS = volatile solids, TSS = total suspended solids, VSS = volatile suspended solids,* PO_4*-P = phosphate phosphorus,* NH_4*-N = ammonium nitrogen*

Parameter	Min	Max	Median	Mean	SD
Conductivity (ms/cm)	0.21	4.9	1.2	1.4	0.84
DO (mg/L)	0.29	2.9	0.44	0.52	0.37
pH	5.00	8.80	7.2	7.1	0.55
Temperature (°C)	28.0	36.0	32.0	32.0	1.4
BOD (mg/L)	110	8 600	1 100	1 700	1 600
TS (g/L)	1.3	130	24.0	31.0	26.0
VS (g/L)	0.73	53.0	14.0	15.0	12.0
TSS (g/L)	0.99	180	19.0	25.0	25.0
VSS (g/L)	0.29	59.0	11.0	13.0	11.0
PO_4-P (mg/L)	1.3	150	18.0	26.0	26.0
TP (mg/L)	73.0	1 900	400	500	340
NH_4-*N* (mg/L)	16.0	670	140	180	120

Overall, data on chemical qualities of faecal sludge samples collected from all sources were not normally distributed. The concentration of all chemical parameters showed large variation in mean and median values and large standard deviation that was almost equal to the mean. The concentrations of all chemical parameters studied in sludge samples from household sources were within similar ranges for both septic tank and cesspit containment systems (Paper I-Table S1). The concentrations of nutrients (NH_4-N, PO_4-P and TP) were in similar ranges for faecal sludge samples from all sources (Papers I and III).

Table 3. *Physicochemical properties of faecal sludge samples collected in Phnom Penh in the dry and rainy season. SD = standard deviation, DO = dissolved oxygen, TS = total solids, VS = volatile solids, PO_4-P = phosphate phosphorus, TP = total phosphorus, NH_4-N = ammonium nitrogen, TN = total nitrogen. p-value <0.05 indicates statistically significant difference between dry and rainy seasons, (-) indicates data not available.*

Parameter	***Both seasons*** (n=42)			***Dry season*** (n=21)					***Rainy season*** (n=21)					***p*-** value
	Median	Mean	SD	Min	Max	Median	Mean	SD	Min	Max	Median	Mean	SD	
Conductivity (ms/cm)	1.5	1.8	0.99	0.62	4.9	1.5	1.8	1.0	0.64	4.5	1.5	1.7	0.98	0.586
DO (mg/L)	0.56	0.56	0.09	0.42	0.82	0.57	0.58	0.08	0.43	0.83	0.53	0.54	0.092	0.157
pH	7.1	6.9	0.60	5.4	8.3	7.1	7.0	0.62	5.5	7.6	7.0	6.9	0.59	0.484
Temperature (°C)	29	29	1.4	27	33	30	30	1.7	28	32	29	29	1.1	0.266
TS (%)	1.9	2.9	2.9	0.52	10	2.1	2.9	2.4	0.30	13	1.4	2.9	3.5	0.261
VS (%)	69	62	18	33	84	72	64	17	13	90	63	61	19	0.517
PO_4-P (mg/L)	-	-	-	10	680	610	100	140	-	-	-	-	-	-
TP (mg/L)	-	-	-	220	2500	230	470	650	-	-	-	-	-	-
NH_4-N (mg/L)	-	-	-	40	680	110	160	140	-	-	-	-	-	-
TN (mg/L)	-	-	-	1,500	3,300	2,000	2,200	650	-	-	-	-	-	-

5.2.2 Heavy metals

The concentrations of heavy metals, classified as essential and non-essential (Paper III) (Table 4). Similarly to physicochemical qualities of faecal sludge, concentrations of heavy metals were not normally distributed, and standard deviation was almost as great as the mean in almost all cases. Mean and median values of metal concentrations in faecal sludge varied widely. In the dry season, mean concentration of heavy metals decreased in the order: Zn>Cu>Ni>Pb>Hg>Cr>As>Cd. However, a slightly different decreasing trend was found in the rainy season: Zn> Cu> Pb> Cr> Ni>Hg>As>Cd. The same distribution shift was observed for all studied elements in individual sample and in both seasons. In both seasons, the two metals present in the highest concentrations were always Zn and Cu, and the two metals present in the lowest concentrations were always As and Cd (Table 4). The concentrations of Pb and Cr were higher than those of Ni and Hg in the rainy season, while the opposite trend was observed in the dry season. Ni was present in the third highest concentration, after Zn and Cu, in the dry season.

5.2.3 Sources of variation in physicochemical qualities of faecal sludge

Differences in containment unit type in terms of lined or unlined, connected or not connected to urban drainage network, water added or no water added during emptying events, only blackwater or mixture of domestic wastewater fractions, number of users (<10, 10-50, and >50 people), and containment unit age (3-10, 10-20 and >20 years) were included in the assessment of sources of variation in physicochemical qualities of the faecal sludge. Water added during emptying events and type of wastewater captured by the containment system were the dominant sources of variation in PO_4-P and NH_4-N concentrations ($p<0.001$). The concentration of TP ($p=0.006$) was significantly influenced by connection to drainage network and type of wastewater captured by the containment unis. Connection to the urban drainage network also had significant impacts on the concentrations of BOD, TS, VS, TSS and VSS (Paper I).

5.2.4 Seasonal variation in faecal sludge from various sources

A significant difference ($p<0.05$) between the wet and dry seasons was detected for all heavy metals except Hg, Ni and Zn (Table 4), but not for conductivity, DO, pH, temperature, TS and VS (Table 3). Overall, however, the mean values of conductivity, DO, pH and temperature were generally lower in the rainy season than in the dry season (Table 3).

Table 4. *Summary statistics on heavy metal concentrations (mg/kg) in faecal sludge samples collected in Phnom Penh in the dry and rainy seasons. All values expressed on a dry mass basis (mg/kg total solids, TS). Values in bold indicate significant difference between the seasons ($p<0.05$)*

Parameter	***Dry season*** (n=21)					***Rainy season*** (n=21)					***p*-value**
	Min	Max	Median	Mean	SD	Min	Max	Median	Mean	SD	
						Non-essential metals					
Arsenic (As)	0.28	5.7	1.1	1.7	1.6	2.8	15	4.4	5.4	3.0	**<0.001**
Cadmium (Cd)	<1[a]	2.3	<1[a]	-	-	<1[a]	2.2	1.1	-	-	**0.011**
Mercury (Hg)	1.1	16	3.7	4.9	3.6	<0.02[a]	16	3.1	5.3	5.1	0.654
Lead (Pb)	1.4	17	10	9.2	3.9	9.1	112	46	49	27	**<0.001**
						Essential metals					
Chromium (Cr)	<1[a]	13	3.8	4.1	2.7	22	72	40	43	13	**<0.001**
Copper (Cu)	15	670	79	120	130	67	280	160	150	61	**0.0062**
Nickel (Ni)	2.5	57	14	21	17	12	30	18	19	5.3	0.102
Zinc (Zn)	810	1 900	1 300	1 200	330	320	4 300	1 600	1 600	900	0.184

[a] Below limit of quantification.

5.3 Flow of resource content in faecal sludge

This section presents the mass flow of faecal sludge after emptying from the containment unit at household level. Quantities of faecal sludge and resource content in faecal sludge were estimated to assess its resource recovery potential.

5.3.1 Disposal sites

Boeung Trabek pumping station and Toul Sampov wastewater canal were the two main faecal sludge disposal sites in Phnom Penh identified in this thesis (see Figure 11). During data collection, there was no faecal sludge treatment plant in the city and Boeung Trabek pumping station was the only authorised disposal site (JICA, 2016; Peal *et al.*, 2015). More disposal sites were identified during data collection, including a public manhole near households from which faecal sludge was emptied and collected, a field near Kob Srov wetland, Toul Sampov wastewater canal, a small canal located around 1 km from Toul Sampov wastewater canal and Boeung Trabek pumping station. The survey also revealed that the majority of emptied faecal sludge in Phnom Penh was sent to Boeung Trabek pumping station (54% of all sludge emptied during the data collection period), although Toul Sampov wastewater canal and a small nearby canal also played a key role in receiving faecal sludge (35%) in the northern part of Phnom Penh. However, a new disposal site found during data collection for Paper III will likely replace Toul Sampov wastewater canal in future. The remaining 11% of faecal sludge emptied and collected by vacuum truck operators went to open fields around Kob Srov wetland and public manholes near source households (Paper II).

Faecal sludge disposed of within the drainage network in Phnom Penh ended up in one of the two main receiving wetlands, Cheung Ek (located in southern Phnom Penh) and Kob Srov (located in the northern part of the city) (Figure 13). An estimated 58% of faecal sludge emptied and collected by vacuum truck operators ended up at Cheung Ek wetland, while the remaining 42% was received by Kob Srov. The average travel distance from source households to Cheung Ek and Kob Srov was 4.3 km (range 0-14 km) and 3.9 km (range 0-13 km), respectively. Manholes in front of households identified as one of the disposal sites had the shortest distance to disposal of the sludge (0 km). Such disposal happened where the household had a manhole located in front of the house and was within the drainage network coverage (Paper

II). The sludge then flowed by gravity within the drainage network to one of the two wetlands.

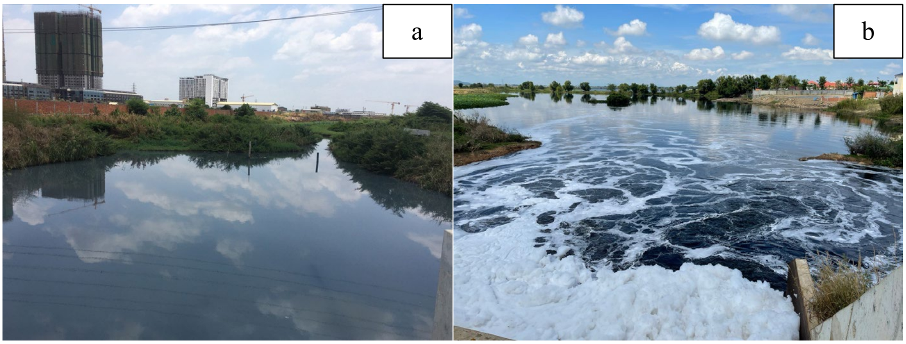

Figure 13. The two natural wetlands near Phnom Penh which are the main recipients of faecal sludge before the final recipient rivers (Bassac and Tonle Sap). (a) Cheung Ek and (b) Kob Srov.

Most discharge events fell within travel distance zones I and II (Figure 14). Most frequently, travel to discharge the emptied sludge during the observation periods happened within zone I travel distance (approximately 53%), while around 40% fell within zone II (Paper II).

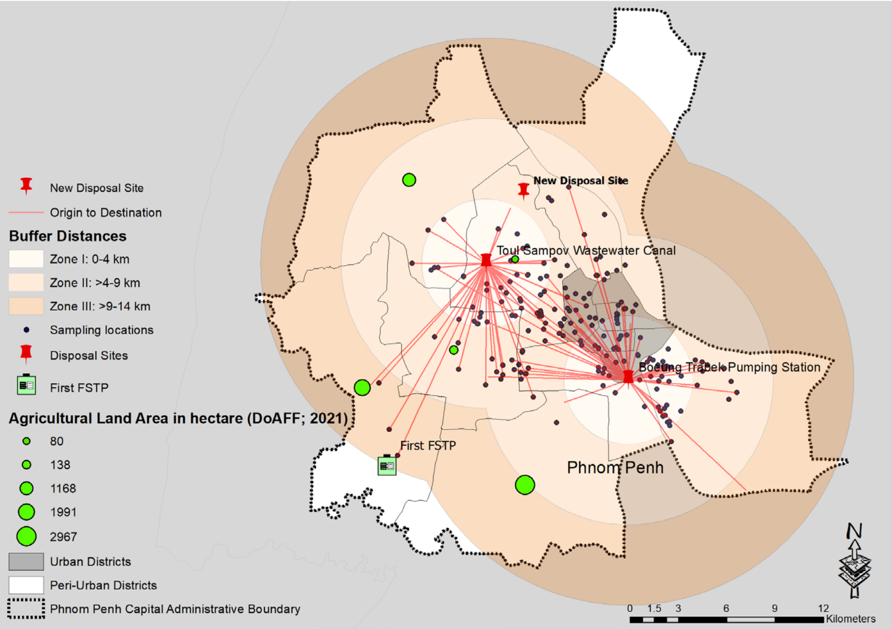

Figure 14. Transport distance zones I-III (within 4, 9 and 14 km) around the two main disposal sites in Phnom Penh identified in Paper II (Toul Sampov wastewater canal and Boeung Trabek pumping station), and the new disposal site identified in Paper III.

5.3.2 Quantities of faecal sludge

Excreta production in all types of containment unit was 600 L/cap/year (Table 5). Based on the results in Paper I, type of containment unit did not significantly influence faecal sludge qualities. Faecal sludge generation (Q_2) and accumulation (Q_3) rates were 22,000 and 110 L/cap/year for all types of containment unit. The total amount of faecal sludge emptied (Q_4) and thus collected in Phnom Penh (Q_5) was 33,000 m^3/year. This was based on the assumption that all faecal sludge emptied was collected, since no manual emptying service was observed and households in Phnom Penh prefer to have mechanical emptying services. Quantitatively, Cheung Ek wetland received around 19,000 m^3/year, while the remaining (14,000 m^3/year) was sent to Kob Srov wetland.

Table 5. *Excreta generation and faecal sludge quantities at different stages along the onsite 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)	600	1,400,000
Faecal sludge produced (Q_2)	22,000	50,000,000
Faecal sludge accumulation (Q_3)	110	33,000
Total faecal sludge emptied (Q_4)	110	33,000
Total faecal sludge collected (Q_5)		33,000
Faecal sludge collected, delivered to Cheung Ek wetland (Q_{5a})	-	19,000
Faecal sludge collected, delivered to Kob Srov wetland (Q_{5b})	-	14,000

5.3.3 Resource quantification

Each individual excreted around 3.1 kg N and 0.45 kg P per year (Table 6). The total amount of nitrogen contained in excreta was estimated to be 950 tons/year and the amount that could potentially remain in faecal sludge was 65 tons/year annually (approximately 7%), and was disposed of in the two main receiving wetlands. Proportionally, around 37 and 27 tons/year of total nitrogen were sent to Cheung Ek and Kob Srov wetland, respectively. Around 9% of total phosphorus (almost 13 tons/year) remained in faecal sludge relative to the amount in excreta. Around 7.5 tons/year of total phosphorus was discharged to Cheung Ek wetland and around 5.5 tons/year to Kob Srov wetland (Paper II).

Table 6. *Estimated amounts of resources (total nitrogen (TN) and total phosphorus (TP)) 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	3.1	950,000	-
TN in faecal sludge	-	-	65,000
TN to Cheung Ek	-	550,000	37,000
TN to Kob Srov	-	400,000	27,000
Total phosphorus in excreta	0.45	140,000	
TP in faecal sludge			13,000
TP to Cheung Ek	-	80,000	7,500
TP to Kob Srov	-	58,000	5,500

[a] Equations (5) and (6)

[b] The population used for this calculation was 306,238, representintg the population using onsite sanitation with experience of emptying their containment unit (Frenoux *et al.*, 2011; Peal *et al.*, 2015; NIS, 2020)

[c] Median TN concentration was 2000 mg/L (Paper III) and median P concentration 400 mg/L (Paper I). Note that it is Q_4 x concentration.

5.4 Treatment technologies

This section presents the assessment steps (screening, MCA, stakeholder discussion and ranking) used to identify sustainable faecal sludge treatment technologies that are appropriate for cities in low- and middle-income countries.

5.4.1 Screening step

Treatment technologies were divided into two groups (primary and secondary) based on their performance. Seven primary and 13 secondary treatment technologies were identified (Paper IV). The feasibility of primary technologies was assessed using defined criteria based on the context of Phnom Penh, namely use of chemicals, energy requirement and process complexity, while reuse potential was also included when assessing the feasibility of secondary treatment technologies (Table 6).

Screening was performed to eliminate non-feasible treatment technologies before moving forward to the MCA step. This screening step resulted in three primary treatment technologies and four secondary treatment technologies. The three primary treatment technologies all involved physical processes (drying bed (planted or unplanted), settling-thickening tank, Geobags). A feasibility study should be conducted for these technologies before implementation, but was beyond the scope of this thesis.

The four secondary treatment technologies that remained after screening were drying bed (solar drying), co-composting, vermicomposting and black soldier fly larvae (BSFL) composting. These were retained in screening due to their high resource reuse potential and lower process complexity than other technologies (Paper IV).

5.4.2 Multi-criteria assessment of secondary treatment technologies

Multi-criteria assessment was based on the assumption that all technologies were operated as designed. The technologies scored differently for the main sustainability criteria (health, environment, economic, socio-technical) with respective to indicators and sub-indicators (Table 7).

Co-composting received the highest score for health criteria, as this technology has high sanitisation efficiency in treatment and, when operated at thermophilic temperature, produces a reuse product that meets Class A biosolids under USEPA part 503 rules and WHO guidelines. Reuse products from other three secondary treatment technologies required further sanitisation treatment (chemical or thermal, extended storage) to reach hygienically safe levels before use in agriculture.

Vermicomposting and BSFL composting obtained the highest score for environmental criteria, followed by solar drying. Since treatment in these three technologies is performed under mesophilic conditions, greenhouse gases (GHGs) emissions are lower. Co-composting received the lowest score, it has the highest potential to emit GHGs.

The top two technologies for economic criteria were solar drying and vermicomposting, followed by co-composting. BSFL composting received the lowest score, as it has the highest investment and operation and maintenance (O&M) costs, despite adding value to reuse products (larvae and compost-like frass).

Co-composting performed best for socio-technical criteria in terms of robustness of technology, followed by solar drying, BSFL and vermicomposting. Co-composting also performed best in terms of public acceptance of reuse products, followed by solar drying and vermicomposting. BSFL composting performed worst of the four technologies, as it is less known to the general public in Cambodia and possibly those in other low- and middle-income countries (Paper IV).

Table 7. *Total score obtained for selected sustainability indicators and sub-indicators in multi-criteria assessment (MCA) of four faecal sludge secondary treatment options for Phnom Penh, Cambodia. Where a five-point score (red=1, amber=2, yellow=3, light green=4, dark green=5) could not be applied to a sub-indicator, a three-point scale was used (1, 3, 5). Treatment technologies: SDry = solar drying, CoC = co-composting, VerC = vermicomposting, BSF = black soldier fly larvae composting, GHG = greenhouse gas*

Indicator	Sub-indicator	Treatment technology				Total score
		SDry	CoC	VerC	BSF	
Health criteria						30
Treatment sanitisation efficiency	Total coliforms/E-coli	3	5	1	3	12
	Faecal streptococci/ enterococcus	3	5	1	1	10
	Helminth eggs	1	5	1	1	8
Environmental criteria						46
Energy requirement	Potential energy demand by treatment system	3	3	5	3	14
Land requirement	Total land area required to operate the system	5	5	5	5	20
Climate impact	GHG emissions from the treatment system	3	1	3	5	12
Economic criteria						38
Investment cost	Total investment cost to build the system	3	3	3	1	10
Operation & maintenance (O&M) cost	Total O&M cost for daily operation	5	3	3	1	12
Reuse product value	Quality of reuse product(s) based on local classification	3	3	5	5	16
Socio-technical criteria						88
Robustness of technology	Level of technology development	3	5	3	3	14
	Capacity to endure shock load-quality of input material	4	3	2	3	12
	Capacity to endure shock load-quantity of input material	4	4	3	3	14
	Resilience to climate change impact-flooding	1	1	1	1	4
Public acceptance of reuse product	Public acceptance of reuse product to grow inedible plants, trees and grass	4	4	4	4	16
	Public acceptance of reuse product to grow food eaten by animals	3	4	4	3	14
	Public acceptance of reuse product to grow food for humans	4	4	3	3	14

5.4.3 Stakeholder discussion and ranking

Local stakeholder opinions were included in weighing sustainability criteria for final ranking of the technologies after MCA. Different stakeholder groups weighted the sustainability criteria differently, *e.g.* public stakeholders weighted environmental criteria higher than other criteria, whereas non-governmental organisations (NGOs) and development partner (DP) stakeholder groups rated institutional criteria highest. However, institutional criteria were excluded from MCA and the final ranking of the four treatment technologies.

Overall, co-composting received the highest normalised total score, so it was ranked as the first-choice technology, followed by solar drying (Table S9 in Paper IV). Vermicomposting was in third place, while BSFL was the lowest-ranking option (Paper IV).

6. Discussion

As part of efforts to address the challenges facing faecal sludge management in cities in low- and middle-income countries, this thesis investigated the management of faecal sludge from waterborne systems, using Phnom Penh as a case study. The resource recovery potential of the faecal sludge was also investigated. Baseline data obtained on the qualities and quantities of faecal sludge produced and the main challenges in current faecal sludge management, such as logistics, opportunities for resource recovery and appropriate treatment technologies for cities in low- and middle-income countries, are discussed in this chapter.

Analysis of the data collected revealed that the faecal sludge generated and collected in Phnom Penh is highly diluted, due to multiple factors (Paper I). As a result, the quantities of faecal sludge and its content of resources available for recovery were relatively low given current management practices (Paper II), limiting the reuse potential. In addition, the elevated concentrations of heavy metals detected in faecal sludge would limit its potential for reuse and the reuse product would not be suitable for use as fertiliser to edible crops in agriculture (Paper III). Solutions to tackle the main faecal sludge management challenges in Phnom Penh were assessed in Paper IV. The findings in this thesis can serve as key inputs for appropriate faecal sludge management planning in Phnom Penh and other cities with a similar context.

6.1 Qualities of faecal sludge and influencing factors

This section discusses factors that contributed to dilution of faecal sludge in Phnom Penh and to variations in the qualities of faecal sludge collected from household sources. Heavy metal contamination and variation between seasons for faecal sludge collected from household and restaurant sources are also discussed.

6.1.1 Physicochemical qualities

The concentrations of chemical parameters in faecal sludge samples collected at household level were at the low end of ranges reported in other studies (Paper I). Multiple factors contribute to the highly diluted faecal sludge in Phnom Penh. Almost all households surveyed have a piped water supply into their premises, meaning that water is easily accessible when needed, leading to great use of water (Paper II). Piped water supply coverage is gradually expanding in Phnom Penh, indicating that water shortage is no longer an issue at household level (PPWSA, 2022). With better availability of water, residents in Phnom commonly use a waterborne system comprising a flush toilet connected to an onsite sanitation containment unit. These waterborne systems probably contribute significantly to the low concentrations of chemical parameters in faecal sludge in Phnom Penh. Water availability and consumption rate have been identified previously as factors influencing the nutrient levels in domestic wastewater (Friedler *et al.*, 2019). Additional water was added to facilitate emptying, since faecal sludge stored in a containment unit for more than three years is difficult to vacuum pump (Chandana & Rao, 2021a), further diluting the faecal sludge and the concentrations of chemical parameters. The containment units of around 82% of households surveyed in Phnom Penh also captured all types of domestic wastewater (Paper II), which could be a further factor in dilution of faecal sludge in the city.

Another factor that most likely contributed to the low concentrations of chemical parameters in faecal sludge was connection of the onsite containment to the urban drainage network, since this allows supernatant to flow freely from the containment unit. It was found that approximately 71% of households surveyed in Phnom Penh had their containment connected to the urban drainage network (Paper II). The faecal sludge that remains in containment units is generally more viscous at emptying. According to Swedish data, approximately 88% of the nitrogen and 67% of the phosphorus contained in excreta derive from urine and only small proportions of these nutrients derive from the solid fraction (Jönsson *et al.*, 2004). Therefore, the nutrient content in the solid fraction is low and the nutrient content in faecal sludge in Phnom Penh is generally lower than that in liquid domestic wastewater fractions.

The supernatant/liquid fraction had a significantly higher nutrient content, which pose risks of eutrophication of water bodies and changes in natural ecosystem functions. With the current management system, nutrient concentrations in the liquid fraction of wastewater in Phnom Penh likely exceed the permissible limit in the Cambodian standard on wastewater discharge to natural water bodies (RGC, 2017). This nutrient content could be captured and become a useful resource for agricultural production, *e.g.* the liquid fraction could be treated and used for irrigation or in the industrial sector. Use of the treated water will depend on the type of treatment technology (Samal *et al.*, 2022). More research is needed to determine the quality of wastewater supernatant and identify the best reuse options in the context of Phnom Penh or other cities.

The mean concentration of TN found in faecal sludge (Paper III) was higher than previously reported values (Ahmed *et al.*, 2019; Afolabi & Sohail, 2017). This may have been due to methodological improvements in TN analysis in this thesis. Total nitrogen concentration is the sum of all nitrogen forms, including organic and inorganic nitrogen. Total ammonia nitrogen (TAN), nitrite and nitrate are the main inorganic forms present and, if a photometric method is used in analysis, all nitrogen in the sample should be converted to nitrate through oxidation. If addition of oxidation reagents is insufficient to convert all organic and inorganic nitrogen into nitrate, the reading obtained will be lower than the actual value. Moreover, high chemical oxygen demand in faecal sludge samples causes interference, inhibiting conversion of organic and inorganic nitrogen into nitrate. Therefore, dilution factors of faecal sludge samples and addition of oxidation reagents were taken into account when analysing TN in faecal sludge samples in this thesis.

Overall, the waterborne system, containment unit emptying by diluting faecal sludge with water, capture of all types of wastewater in the onsite containment unit and connection to the urban drainage network were identified as the key contributors to the low concentrations of chemical parameters in faecal sludge in Phnom Penh. Those four factors are also likely to be relevant in other cities in low- and middle-income countries, and would result in similar concentration ranges in faecal sludge produced in those cities. For instance, 96% of households in Vietnam and 85% of households in Indonesia have access to a flush toilet and the majority of those toilets (75% in Vietnam and 66% in Indonesia) are connected to septic tanks or pits (WSP, 2015). The situation is likely to be quite similar in other countries in the region. Connection of onsite containment units to an urban drainage network is also common in some of the neighbouring countries, *e.g.* Vietnam has a combined sewerage system with septic tanks connected to the drainage network (WSP, 2015). With greater availability of water at household level, emptying and transportation operators are likely to use water to transform highly viscous sludge into a slurry that can easily be pumped out of the containment unit.

6.1.2 Factors influencing the physicochemical qualities of faecal sludge

Different factors contributed to the statistically significant differences observed for some physicochemical parameters in faecal sludge in Phnom Penh. Types of domestic wastewater captured by containment units significantly affected the concentration of TP in faecal sludge, *e.g.* containment units that only captured blackwater had significantly higher TP concentrations than units which captured all types of wastewater. The opposite trend was observed for BOD concentration. Addition of extra water during emptying events significantly lowered the concentrations of NH_4-N and PO_4-P in faecal sludge. The concentrations of BOD, TS, VS, TSS, and VSS were significantly higher, and NH_4-N and PO_4-P concentrations were significantly lower, in faecal sludge from containment units connected to the urban drainage network than in sludge from non-connected units (Paper I). However, all models developed to explain the contribution of these factors to the variation in faecal sludge qualities had quite low R^2 and adjusted R^2 values, indicating that they did not fully explain the variation observed (Paper I).

Variables that did not contribute significantly to the variation in faecal sludge were containment unit type, lined/unlined containment unit, number of users and containment unit age. There are likely two reasons for this, *i.e.* lack of a legal framework and regular monitoring of onsite containment units by local government. Residents in Phnom Penh reported that they need to have their containment unit emptied only when it is full (35%) or clogged (57%) (Paper II), meaning that there is no regular emptying requirement. This would lead to poor performance of all types of onsite containment systems in Phnom Penh. It could possibly also be the case in other cities where a policy framework for faecal sludge management is lacking. There is a local sub-decree in Phnom Penh that requires installation of a septic tank for newly constructed residences, but no specific standard drawing of the required system is provided (JICA, 2016). Thus, the design of the sanitation system constructed will depend fully on the local contractor. Similarly, countries like Vietnam and Indonesia have few policies in place to address faecal sludge management challenges and management of onsite sanitation system in those countries is solely the responsibility of household owners (WSP, 2015).

6.1.3 Heavy metals

Multiple sources can have contributed to the elevated concentrations of heavy metals observed in faecal sludge in Phnom Penh, and in other cities with comparable sanitation contexts. For instance, the concentrations of almost all metals analysed were generally higher in the rainy season than in the dry season, probably due to contaminated surface run-off entering the system during storm events. Containment units that capture mixed wastewater can also be expected to contain higher concentrations of heavy metals than those collecting only blackwater, due to the higher metal concentrations in greywater (Vinnerås *et al.*, 2006). The use of heavy metal-containing materials in different activities in society also affected the metal concentration in faecal sludge (Paper III). However, arsenic could be a natural occurrence from groundwater contamination in peri-urban areas of Phnom Penh (Berg *et al.*, 2007).

There are two groups of heavy metals, essential and non-essential. The essential heavy metals (Cr, Cu, Ni and Zn) are required in the diet and biologically used by enzymes. The non-essential heavy metals (As, Cd, Hg and Pb) are toxic to organisms exposed to even trace amounts (Slobodian *et al.*, 2021). However, overexposure to either group of heavy metals can pose a health risk (Vinnerås *et al.*, 2006). The concentrations of all heavy metals in faecal sludge samples collected in Phnom Penh fell within the acceptable range set in guidelines issued by USEPA (USEPA, 1994) and in the European Council Directive (CD, 1986) on use of sludge as biosolids for land application in agriculture. However, the concentrations of mercury and zinc exceeded the Cambodian permissible limit for organic fertiliser (MAFF, 2012) and the Swedish limit for compost (Sharma *et al.*, 2017), while the concentrations of other metals were still within the permissible range (Table 8).

Table 8. *Mean concentration ±standard deviation (mg/kg total solids) of heavy metals in faecal sludge in Phnom Penh, and corresponding limits set in different standards and guidelines on heavy metals. Bold indicates that the concentration exceeds the permissible limit in the Cambodian standard for organic fertiliser and Swedish limit for compost*

Parameter	Mean value from both seasons	Cambodian standard for organic fertiliser[1]	Compost in Sweden[2]	Council Directive 86/278 EEC[3]	USEPA Limits for Biosolids[4]
Arsenic	3.6±3.0	10	-	-	41
Cadmium	<1[a]	5	3	20-40	39
Mercury	**5.1±4.3**	0.15	3	16-25	17
Lead	29±28	100	150	750-1200	300
Chromium	23±22	50	150	-	1200
Copper	130±100	300	150	1000-1750	1500
Nickel	20±12	50	50	300-400	420
Zinc	**1 400±690**	1000	500	2500-4000	2800

[1](MAFF, 2012) [2](Sharma *et al.*, 2017) [3](CD, 1986). [4](USEPA, 1994).

However, the concentration of heavy metals in relation to the nutrient content indicated that the treated faecal sludge was not safe for reuse as fertiliser in agriculture (Table 9). All heavy metals in faecal sludge samples except cadmium and chromium were present in higher concentrations than in mineral phosphorus fertiliser (Paper III). Faecal sludge from Phnom Penh also contained high concentrations of heavy metals in relation to phosphorus recovered compared with other waste materials, with fresh urine having the lowest heavy metal concentration (Table 9). Paper I showed that faecal sludge in Phnom Penh was highly diluted and thus the nutrient concentration was low, meaning that more sludge would be needed to achieve the required amount of nutrients (kg P per ha) for crops in agriculture. Applying greater quantities of the sludge to agricultural land would also mean adding more heavy metals, leading to heavy loads in agricultural soil and possibly contamination in the food chain. The metals in the sludge derived from non-food domestic sources, and thereby represented novel inputs to agriculture, whereas if the source had been food the metals in the sludge would have represented recycled existing heavy metals.

Overall, the findings in this thesis indicate that heavy metal contamination of faecal sludge is an area of concern and must be considered when planning for reuse of treated faecal sludge. Heavy metal contamination of faecal sludge is likely to occur also in other cities in low- and middle-income countries where similar onsite sanitation systems exist.

Table 9. *Mean concentration (mg/kg phosphorus (P)) of heavy metals in faecal sludge in this thesis, and in other type of waste fractions, compared with that in mineral P fertiliser. Values in bold indicate higher concentration of heavy metal in sludge than in mineral P fertiliser*

Type of waste	As	Cd	Hg	Pb	Cr	Cu	Ni	Zn
Faecal sludge[1]	**170**	57	410	**860**	390	10000	**1800**	**111000**
Fresh urine[2]	-	0.7	1	2	10	101	7	45
Faeces[3]	-	20	-	40	40	2186	148	**21312**
Urine+ faeces[3]	-	7	-	15	20	797	54	**7146**
Farmyard manure[3]	-	16	-	**124**	463	3537	**427**	**18049**
Sewage sludge[4]	-	46.9	-	**1108**	1072	13360	**617**	**19793**
Mineral P fertiliser[5]	123	82.7	-	55.3	1100	-	190	2290

[1](Radford & Sugden, 2014) [2](Vinnerås *et al.*, 2006) [3](Jönsson *et al.*, 2004) farmyard manure from organic cattle in Sweden. [4](WHO, 2006). [5]Mineral fertiliser samples in 12 European countries (Nziguheba & Smolders, 2008).

6.2 Current trends in sanitation management

This section describes current practices in faecal sludge management from collection at sources to final disposal. Degradation of natural wetlands, general practices in onsite containment management and logistics of faecal sludge management are discussed.

6.2.1 Degradation of natural wetlands

Wastewater generated in central areas of Phnom Penh is discharged mainly into Cheung Ek wetland though the existing combined drainage network. Water environments around Phnom Penh have been seriously impaired by this practice, due to insufficient maintenance of household containment units, dumping of faecal sludge and unregulated land reclamation and city development, which has reduced the natural purification capability of the wetland (JICA, 2019). A 5000 m^3/day pilot wastewater treatment plant, located to the northeast of Cheung Ek wetland, is under construction and is expected to start operation in early 2024, which will lower the burden on Cheung Ek wetland in handling and treating city wastewater. In the past, Cheung Ek wetland was an effective nature-based treatment system, reducing pollutant loads in Phnom Penh wastewater during the dry season before reaching the Bassac river (Sovann *et al.*, 2015; Visoth *et al.*, 2010). Ongoing urban expansion and land reclamation, involving infilling up to 22% of Cheung Ek wetland, is expected to reduce the treatment efficiency of this natural treatment system (Irvine *et al.*, 2015). However, other treatment options are being considered, *e.g.* a new wastewater treatment plant with capacity of 282,000 m^3/day is expected to be constructed between 2031 and 2040 (JICA, 2019).

Faecal sludge is managed as wastewater in Phnom Penh and ends up in the same receiving reservoir. With the current urban development and land reclamation plans, the area of the two nearby wetlands will be smaller in future (JICA, 2019; RGC, 2019). The current pre-treated trickling filtration (PTF) system, the first wastewater treatment plant in the city, is not designed to handle faecal sludge or to treat all wastewater generated in the whole city.

6.2.2 General practices in relation to sanitation management

As mentioned, there is no standard design in place for onsite sanitation systems at newly built residences in Phnom Penh, so construction of onsite systems is based on suggestions from local constructors and decisions by house owners. This has resulted in wide variation in the type of onsite sanitation systems in Phnom Penh. For instance, around 82% of local residents surveyed in Paper II reported that their onsite containment unit captures all types of wastewater. They also reported using different types of onsite containment units (two types of cesspits and two type of septic tanks), made from different materials (Paper I).

Water is commonly used for anal cleansing, but some residents reported using tissue for wiping and disposing of it in a trash bin with other solid waste materials (Paper II). This practice is different from that in *e.g.* some African countries. For instance, a study on dry sanitation systems in Shackleton, Zimbabwe, revealed that people used newspaper and shelled maize cobs for anal cleaning and disposed of these in the toilet, a practice that resulted in high concentrations of COD, BOD, TS and VS in faecal sludge (Changara *et al.*, 2018).

Regular emptying is currently not required for onsite containment units in Phnom Penh, so households use an emptying service only when the containment unit is full or clogged (Paper II). This practice leads to poor performance of the sanitation system, which is designed to pre-treat the wastewater *in situ*. The faecal sludge is currently handled as wastewater, which results in heavy loads of pollutants to nearby natural wetlands, as discussed above. A similar situation will arise in cities in neighbouring countries in which there is no standard design for onsite containment system and no requirement for regular emptying in place.

6.2.3 Logistics in faecal sludge management

In addition to data on qualities and quantities of faecal sludge, provision of efficient collection and transportation to avoid indiscriminate disposal is key to designing safely managed sanitation systems (Kinobe *et al.*, 2015). Despite the problems caused by indiscriminate disposal, it is common practice around the world. For instance, <50% of faecal sludge generated in urban areas of sub-Saharan Africa is collected and only half of the collected amount is sent to a central treatment plant (Koné & Strauss, 2004). The remainder of the collected sludge is generally indiscriminately disposed of in the surroundings or unsafely used in agriculture (Klingel *et al.*, 2002). A recent study in 39 countries reported that only 35% of emptied sludge is transported to treatment plants, with the rest discharged into open environments (Peal *et al.*, 2020).

Travel distance has been identified as one of the factors resulting in indiscriminate disposal of faecal sludge in the surrounding environment (Murungi & van Dijk, 2014). In many cities in Africa and Asia, mechanical and semi-mechanical emptying are the most common technologies (Chowdhry & Kone, 2012). Mechanical emptying is the most common method in around 80% of communities in low- and middle-income countries in Asian (Conaway *et al.*, 2023). The emptying and transportation operators in Phnom Penh preferred travel distance within 9 km (Paper II). However, the recently built first faecal sludge treatment plant in Phnom Penh, which is designed to treat all faecal sludge generated in the city, is located around 20 km from the two main disposal sites identified in this thesis (Paper II). It is questionable whether all faecal sludge will actually end up at this designated treatment plant, as this will involve long transport distance from households located in central city areas, and there is a high risk that indiscriminate disposal will continue. Other studies have found that the longest sustainable transport distance is 15-25 km (Sagoe *et al.*, 2019) and that there is a high risk of indiscriminate disposal if travel distance to the treatment plant is too long (Sagoe *et al.*, 2019). Thus, it is likely that in future, Boeung Trabek pumping station will still play a role as a faecal sludge disposal site for sludge collected from households around that area, based on the findings in Paper II. These are important findings for sanitation sector planners when deciding on the location of any new treatment plant.

Optimisation of faecal sludge logistics would greatly reduce transportation cost, time and impacts on traffic (Schoebitz *et al.*, 2017). However, access to faecal sludge treatment is always a great challenge for densely populated cities in many low- and middle-income countries. There are a few alternatives available while still keeping the transport distance from source to treatment plant as short as possible. Establishment of multiple transfer stations with onsite dewatering units within a city would reduce indiscriminate disposal of faecal sludge, as it would reduce the transportation cost to a central treatment plant (Schoebitz *et al.*, 2017). In the case of Phnom Penh, Boeng Trabek pumping station, an appropriate location along Toul Sampov wastewater canal and the new disposal site identified in Paper III would be appropriate locations for transfer stations. The supernatant could then easily be sent to the nearby wastewater treatment plant for further treatment and reuse. Another alternative could be introduction of a regular desludging schedule, *i.e.* an appropriate interval for onsite containment unit emptying to households, which would provide benefits for all stakeholders along the entire service chain (Singh *et al.*, 2022). This measure has been included in the 2035 faecal sludge management strategy for Phnom Penh (PPCA, 2021). Regular desludging would reduce local environmental pollution by avoiding containment unit overflow or clogging during the rainy season, thereby preventing faecal contamination of the environment and the associated health risk (Okaali *et al.*, 2022), and would also improve the performance of the septic tank system at individual household. However, to enable regular desludging, the local government would need to have good collaboration and strong engagement with private emptying and transport service providers (Singh *et al.*, 2021). It would also need to carry out field studies to determine the appropriate interval between emptying, as this will relate to number of users and containment unit size. However, there is no one-size-fits-all solution for service provision of faecal sludge emptying and transportation in a city. The findings presented here on the logistics of faecal sludge removal in Phnom Penh (preferred sludge transport distance <9 km) could be tailored to address faecal sludge transportation challenges in similar cities elsewhere.

6.3 Quantities of faecal sludge and resource recovery potential

In addition to the low nutrient concentrations in faecal sludge in Phnom Penh (Paper I), the quantities of faecal sludge generated annually were low owing to the low emptying frequency at households (Paper II). According to PPCA (2021), the emptying frequency is on average once every 9.5 years and occurs mostly during the rainy season and when backflow occurs. The same study showed that the emptying frequency is not related to type of containment unit or to containment unit size. Overall, a total of 65 tons of nitrogen (around 7% of total nitrogen in excreta) and 13 tons of phosphorus (around 9% of total phosphorus in excreta) could be recovered from faecal sludge in Phnom Penh annually. However, these total recoverable amounts are quite low compared with the amount of fertiliser needed in the agricultural sector in peri-urban areas of Phnom Penh, where approximately 1460 tons of nitrogen and phosphorus fertiliser are used annually according to reports by a local NGO called GRET. In addition, the faecal sludge generated is contaminated with heavy metals (Paper III), which limits its resource recovery potential. Alternative uses of nutrients recovered from faecal sludge to avoid re-introducing risks to the environment exist, as discussed in Paper III. Thus while resource recovery from faecal sludge does not seem economically feasible based on the quantities of nutrients that could be captured, pollution load to the natural wetlands near Phnom Penh could be minimised by introducing alternative uses.

6.4 Alternatives for sustainable faecal sludge management

Owing to concerns about the elevated levels of heavy metals in treated faecal sludge in Phnom Penh, the sludge cannot be recommended for use as a fertiliser in food production. These concerns are even greater for faecal sludge collected in the rainy season, compared with the dry season (Paper III). The three alternatives that should be considered when planning future faecal sludge management in Phnom Penh and other cities with high heavy metal contamination in faecal sludge are (i) reuse of treated faecal sludge as a soil conditioner/fertiliser for grass and flowers in city parks, (ii) implementation of upstream source prevention and (iii) introducing source separation systems. Implementation of any of these options would depend on stakeholder visions for faecal sludge management in a given city. Each is discussed in greater detail below.

6.4.1 Use of treated faecal sludge as soil conditioner

To tackle the current challenges in faecal sludge management in Phnom Penh with minimal changes in infrastructure, a short-term solution would be to reuse treated faecal sludge as a soil conditioner to grow inedible plants, trees and grass (Figure 15). Paper IV evaluated four sustainable faecal sludge treatment alternatives for this purpose (solar drying, co-composting, BSFL composting and vermicomposting).

Co-composting ranked top among these technologies, but it requires addition of other feedstock (*e.g.* organic fraction of municipal solid waste) as co-substrate. Since faecal sludge in Phnom Penh has elevated concentrations of heavy metals, to avoid cross-contamination of organic wastes co-composting should not be implemented.

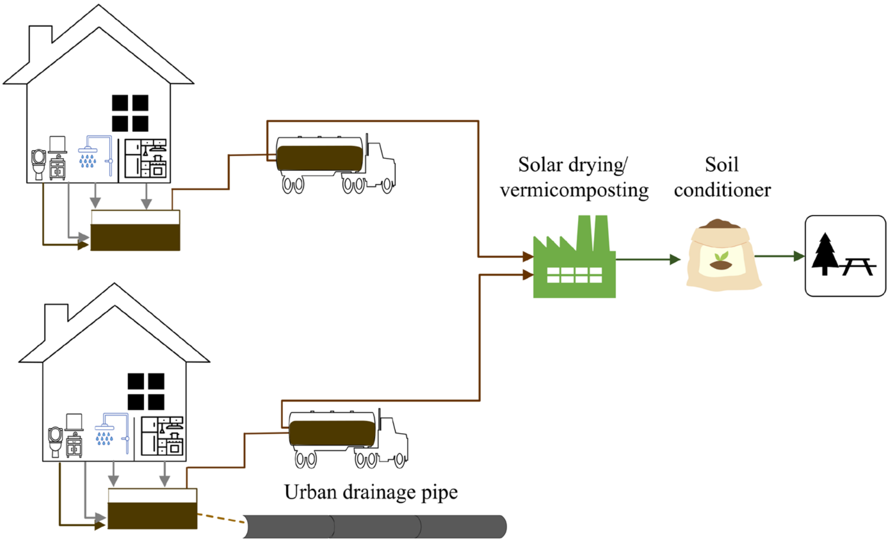

Figure 15. Short-term solution for faecal sludge management in Phnom Penh and similar cities, where all faecal sludge is collected and sent to a centralised treatment plant (for solar drying/vermicomposting). The reuse product could be used as a soil conditioner in city parks.

Solar drying would produce a biosolids product that meets the class B pathogen requirement set by USEPA (Bennamoun, 2012), meaning that it would be suitable for application to growing non-edible plants such as grass and flowers in public green space. This option would achieve greater public acceptance for reuse of faecal sludge than other reuse options (Dirix *et al.*, 2021). Options such as use of biosolids to grow food eaten by animals and food for humans met with low acceptance among the general public in Paper IV. Solar drying is simpler than the other three technologies in terms of operation and maintenance and can treat sludge with a wide range of solids content (Tayler, 2018). It also uses free solar energy, which can reduce the cost of operation (Bennamoun, 2012). It is applicable for a city like Phnom Penh and other tropical cities. However, this technology achieves higher efficiency in volume reduction in summer than in winter (An-nori *et al.*, 2022).

Biological treatment processes such as BSFL composting and vermicomposting would produce compost of similar quality to co-composting, which would be suitable for use on inedible plants. In addition, BSFL and vermicomposting produce larvae and earthworm biomass, resulting in higher economic returns than solar drying technology. However, the highly heavy metal-contaminated feedstock would limit use of the larvae as animal feed (Wang & Shelomi, 2017), although this concern is less critical for lead and zinc (Diener *et al.*, 2015). While BSFL have been found to exhibit strong tolerance to high concentrations of copper and cadmium in feedstock, both metals can still disturb the diversity of microorganisms in the intestine of the larvae (Wu *et al.*, 2020). Similarly, vermicomposting has been shown to decrease the mobility of all heavy metals in sewage sludge feedstock (He *et al.*, 2016). However, these heavy metals remain in the residual fraction (He *et al.*, 2016; Shahmansouri *et al.*, 2005). Another study found a similar reduction in bioavailability of metals in vermicomposting of various municipal and industrial wastes (Swati & Hait, 2017). Substantial bioaccumulation of heavy metals in earthworms after 14 days of vermicomposting has been demonstrated, suggesting that this technology is an efficient method for heavy metal-contaminated feedstocks such as soils (Aleagha & Ebadi, 2011). However, use of earthworm biomass produced from elevated heavy metal feedstock needs to be further investigated to ensure safe reuse.

Overall, solar drying and vermicomposting would be better short-term treatment technologies for faecal sludge in Phnom Penh and other countries than co-composting and BSFL composting. However, decisions on the best technologies should also be based on other sustainability criteria and the trade-offs for sector stakeholders.

6.4.2 Implementation of upstream source prevention

Upstream source prevention is a measure that could prevent heavy metal loads entering onsite containment systems, as part of a medium-term solution for faecal sludge management. Different options or combinations of options can be used for upstream pollution prevention, including: zone classification based on drainage network coverage versus no coverage; disconnecting onsite containment units from the urban drainage network; and an information campaign to reduce unwanted inputs to onsite containment systems (Figure 16). The zone classification option would involve separating the faecal sludge collected into different categories according to whether it is extracted from the drainage network or from a non-drainage network coverage zone, since this thesis speculated that faecal sludge collected from the non-drainage network coverage zone will have low/negligible concentrations of heavy metals and hence higher reuse potential. Disconnection of onsite containment units from urban drainage network would keep the containment unit free from backflow of urban run-off, which can be a source of heavy metal contamination (Paper III). A campaign to raise awareness among local residents could be easily conducted, to attract their attention and ensure their participation in preventing pollution entering the containment units. However, implementing all three alternatives in combination would require collaboration between stakeholders according to their mandates. For instance, the local department of public work and transportation should be able to classify the areas with and without urban drainage network coverage. According to interviews with sector stakeholders, no permission is required for connection to the urban drainage network and any household located within the drainage network coverage area can simply do so. Such connection to the urban drainage network would need to be prohibited for newly constructed households, *e.g.* it could be a condition in the construction permit. A public campaign highlighting “do and don’t” actions as regards onsite containment should be held regularly by the local authority.

If upstream source prevention were to be implemented, the faecal sludge generated would have lower concentrations of heavy metals than in the current situation. The treated faecal sludge from this medium-term solution would have higher reuse potential, as it would be expected to have low/acceptable levels of heavy metal contamination. For instance, it has been found that treated faecal sludge from bench-scale unplanted filter beds in Kumasi, Ghana, contains low levels of heavy metals (mg/kg TS), *e.g.* Cu: 0.081-0.157; Pb: 0.009-0.032; Cd: 0.036-0.092; Zn: 0.026-0.254 (Kuffour *et al.*, 2013). Thus, the biosolids from that sludge would have much lower/negligible concentrations of heavy metals than the faecal sludge generated in Phnom Penh (Paper III). It is possible that similarly low concentrations of heavy metals in faecal sludge in Phnom Penh could be achieved by implementation of upstream source prevention. The biosolids would then have potential use as a fertiliser for edible crops in agriculture, by meeting requirements in the local standard for organic fertiliser (MAFF, 2012) and in WHO and USEPA guidelines on the use of biosolids in agriculture (WHO, 2006; USEPA, 1994). Co-composting appeared to be the most appropriate treatment technology in terms of multiple sustainability criteria (Paper IV). Most importantly, treated biosolids from the co-composting process meet the Class A pathogen limit set by USEPA and WHO guidelines for safe reuse.

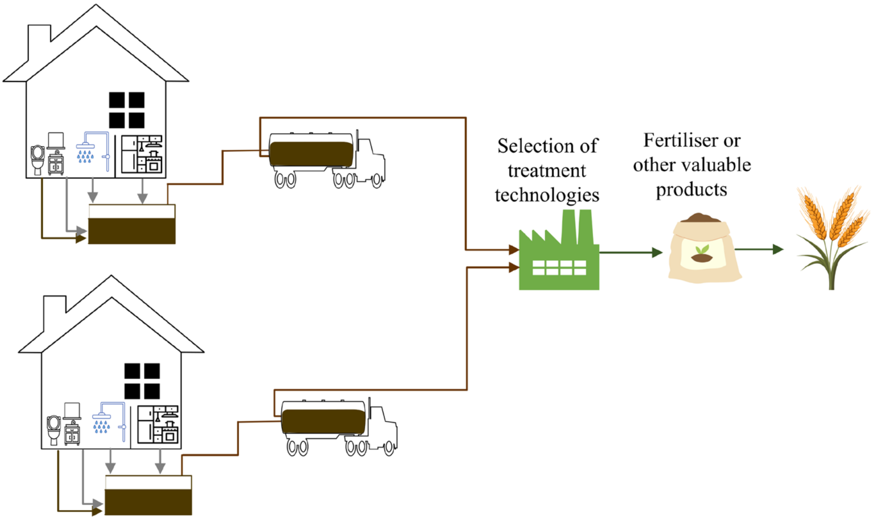

Figure 16. Medium-term solution for faecal sludge management in Phnom Penh and similar cities, where only faecal sludge collected from containment units not connected to the drainage network and capturing only blackwater or mixed wastewater is sent to a centralised treatment plant. The reuse product could be reused as fertiliser.

From an economic incentive perspective, BSFL composting and vermicomposting would be better treatment options than co-composting, as they would provide more high-value reuse products (Lalander *et al.*, 2017; Huis *et al.*, 2013). Both would also be more economically viable than co-composting and solar drying. However, for the biosolids produced (frass and vermicompost) to meet the class A pathogen limit, additional treatment would be needed, for instance nine days of thermophilic composting of feedstock followed by 2.5 months of vermicomposting would give complete pathogen inactivation (Nair *et al.*, 2006). For the solar drying option, 15% of lime on a TS basis would need to be added to dewatered faecal sludge before drying in covered drying beds to achieve class A pathogen inactivation in treated biosolids (Kamil Salihoglu *et al.*, 2007). However, pre-treatment or post-treatment of treated biosolids from the three treatment technologies would add cost, and hence the overall treatment cost would be increased.

6.4.3 Implementation of source separation system

Introducing a source separation system would be a long-term solution for faecal sludge management. Source separation involves separating different fractions of domestic wastewater before sending them to a centralised/decentralised treatment plant. This alternative provides higher benefits in resource recovery potential compared other options, as it recovers nutrients without dilution. It also improves treatment capacity by reducing treatment costs at the centralised wastewater treatment plant, supports local food security and increases the efficiency of nutrient recovery ((McConville *et al.*, 2017). Since there are different types of domestic wastewater fractions (blackwater and greywater) (Friedler *et al.*, 2019), different options for source separation could also be considered, *e.g.* separation of blackwater from greywater, or separation of urine from faeces (Figure 17).

Source separation of blackwater from other waste streams has already been implemented in some cities. For instance, a ‘three pipes out’ system has been installed in Oceanhamnen district, Helsingborg, to separate blackwater (from vacuum toilet), greywater, and food waste from kitchen grinders, in order to optimise nutrient recovery and the treatment system. The system was built to accommodate around 320 apartments with approximately 1800 people (www. run4life-project.eu). A recent comparative study of two source separation systems (blackwater separation and urine separation) and the conventional wastewater system in Hiedanranta district, Finland, found that nutrient recovery from the source separation systems was up to 10-fold higher than from the conventional system (Lehtoranta *et al.*, 2022). Like upstream source prevention, source separation would generate faecal sludge with low/negligible concentrations of heavy metals, but high concentrations of nutrients. It therefore has high potential for reuse as fertiliser. Selection of faecal sludge treatment option would be similar to that in upstream source prevention. In practice, however, nutrients would be lost during the dewatering process, so nutrient recovery would probably not be as high as indicated in Lehtoranta *et al.* (2022). To capture the complete nutrient content in blackwater, treated blackwater could be used in agricultural fertigation. There are different technologies available for effluent reuse in fertigation, with the optimum treatment depending on site-specific factors and local acceptance (Mainardis *et al.*, 2022).

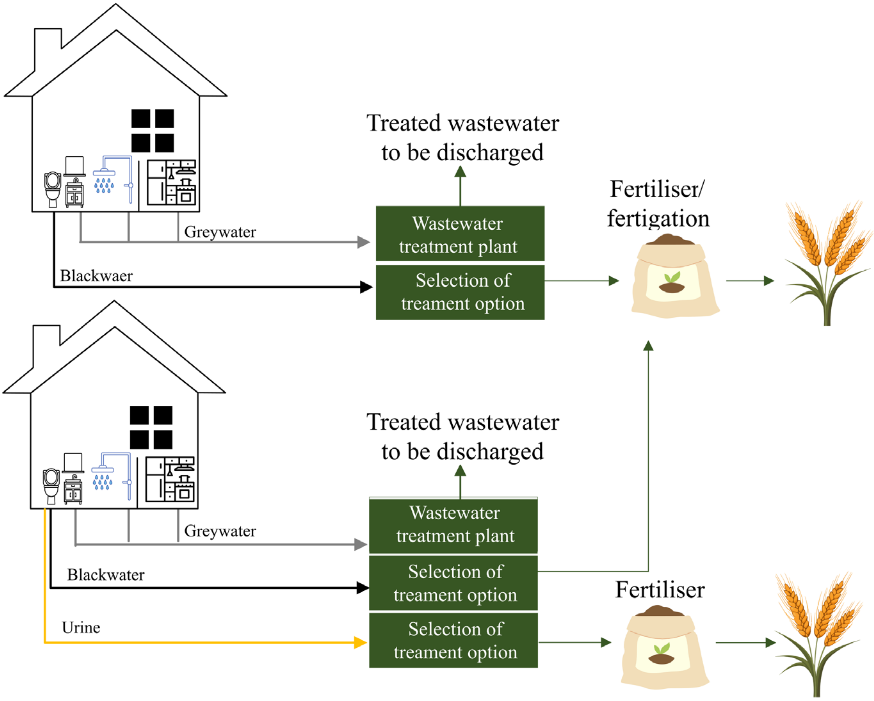

Figure 17. Long-term solution for faecal sludge management in Phnom Penh and similar cities, where blackwater separated from greywater and urine collected from source separating systems are treated separately and dried urine/reuse product is reused as fertiliser. Other types of domestic wastewater could be sent to a treatment plant and treated accordingly.

Another alternative for source separation is to introduce either a urine-diverting dry toilet (UDDT) or urine-diverting flush toilet (UDFT), both of which separate urine and faeces at the time of excretion. The UDDT system allows faeces to dehydrate and recovers urine for beneficial uses (Tilley *et al.*, 2014). This dry sanitation system is suitable in any area, especially where water is scarce, groundwater levels are high and there are rocky areas (Mkhize *et al.*, 2017). Many UDDTs have been installed in different places globally, *e.g.* 80,000 UDDT units have been installed in Durban, South Africa (www.susana.org) and a total of 85, 1052 and 679 UDDTs have been installed in Vietnam, Malawi and Bangladesh, respectively, in a recent ecological sanitation project (Harada, 2022). The reuse product from UDDT systems has high fertiliser value, since urine is the major source of nutrients in domestic wastewater fractions (containing 79% of all N and 47% of all P) (Friedler *et al.*, 2019). Two approaches are available for nutrient management in urine after source separation: treatment of urine on-site or transport to a centralised treatment plant. Onsite technology may be more cost-effective, as having different pipes to collect different wastewater fractions increases the investment cost (Larsen *et al.*, 2009).

The reuse products from urine-diverting toilets are urine and faeces. The urine collected from source separation systems is a good source of nutrients and can be used as liquid fertiliser for agriculture after treatment (McConville *et al.*, 2020b; Tilley *et al.*, 2014). Different technologies are available for urine treatment for reuse, such as nitrification and distillation of urine and alkaline dehydration of urine (McConville *et al.*, 2020b).

While source separation systems have many benefits, major changes in existing infrastructure are required for their implementation. Ultimately, the feasibility of implementation will depend on local conditions (Lehtoranta *et al.*, 2022) and the sustainability of the system will depend on acceptance by users and proper maintenance of the system (Mkhize *et al.*, 2017). The value of faeces and urine as fertiliser is not a driving force for local people to use UDDT (Harada, 2022). Therefore, further investigation is needed on acceptance of urine-diverting toilets by local people and sanitation stakeholders. Local studies are also needed to identify the appropriate urine treatment technologies for a specific context.

7. Conclusions

Planning for proper faecal sludge management needs to cover the entire sanitation service chain, from onsite containment to final disposal/reuse. The following conclusions were drawn in this thesis as regards proper faecal sludge management in Phnom Penh and possibly in other cities with similar onsite sanitation settings:

- Qualities of faecal sludge in Phnom Penh were at the low end of the reported range. The faecal sludge contained low concentrations of nutrients as a result of characteristics of the onsite containment systems, *i.e.* waterborne system, water added during emptying events, containment unit captured mixed domestic wastewater fractions and connection to the urban drainage network in some cases. Other cities in low- and middle-income countries with similar onsite sanitation and urban drainage systems could also have low concentrations of nutrients in faecal sludge, but collection of site-specific baseline data is critically important when planning for faecal sludge management at citywide scale.
- With the current general practices and low emptying frequency of onsite containment units in Phnom Penh, only low total quantities of nutrients can be recovered from faecal sludge, indicating low reuse potential in economic terms. However, other benefits arising from resource recovery are critically important, such as environmental and public health protection.
- The key challenge in faecal sludge management in Phnom Penh is to prevent indiscriminate disposal of faecal sludge, *e.g.* owing to unfavourable logistics. In Phnom Penh, most emptying and transportation operators prefer to travel a maximum of 9 km from source household to the discharge site for the sludge. Therefore, alternatives that reduce transport distance should be considered when selecting locations for new treatment plants, to avoid indiscriminate

disposal of faecal sludge and to safeguard public health and protect the environment. Similar challenges may exist in other cities experiencing rapid urbanisation and with no or limited faecal sludge treatment capacity or long transport distance from source household to a centralised treatment plant. The travel distance preferred by operators in Phnom Penh provides guidance on centralised treatment plant location.

- Faecal sludge in Phnom Penh contains elevated concentrations of heavy metals which, in combination with the low nutrient content, limit the reuse potential. However, resource recovery would still provide benefits for the environment and human health. There are three main options to avoid heavy metal accumulation in soil and uptake by plants if a more circular system is applied. These are: use of biosolids as a soil conditioner to grow non-edible plants; upstream pollution prevention; and source separation of household wastewater fractions.
- The list of resource recovery options developed in this thesis can be a useful starting point for sector stakeholders in other cities in low- and middle-income countries when planning faecal sludge treatment. The criteria used in screening different resource recovery options were based on the Phnom Penh context, but could be employed for screening of treatment technologies in other cities in a similar situation as regards *e.g.* chemical and energy prices.
- Sustainability criteria, indicators and sub-indicators used for assessing different treatment technologies were based on the Phnom Penh context, but could serve as inputs for sector stakeholders tasked with selecting treatment technologies for faecal sludge and wastewater management in other similar cities.

8. Future research

This thesis identified some of the current challenges in faecal sludge management and resource recovery potential in Phnom Penh and the findings can be extrapolated to other cities in low- and middle-income countries with a comparable sanitation situation. Future studies in this specific research field should investigate:

- Supernatant from onsite containment units in Phnom Penh that are connected to the urban drainage network and discharge free-flowing supernatant: this liquid fraction has high potential for use in irrigation or fertigation, as it contains high concentrations of plant nutrients. Studies are needed to investigate the availability of these plant nutrients and to identify treatment technologies to remove unwanted pollutants before reuse.
- Limiting indiscriminate disposal: this thesis found that travel distance is one of the key factors leading to indiscriminate disposal, but did not identify any clear-cut solution to prevent indiscriminate disposal, which likely takes place even when a faecal sludge treatment plant exists. Future studies should focus on key enablers and barriers to safe faecal sludge emptying and disposal.
- Identifying sources of heavy metals: this thesis found that mercury and zinc concentrations in faecal sludge generated in Phnom Penh exceeded the Cambodian limit for organic fertiliser and the Swedish limit for compost. This shows that faecal sludge from onsite containment units is not always safe for reuse, especially in cities such as Phnom Penh with no upstream pollution control. Sanitation city planners in low- and middle-income countries should conduct pre-studies on heavy metal concentrations, especially metals listed in national fertiliser standards, to avoid re-introducing risks to the environment and public health when reusing faecal sludge.

Moreover, studies to identify the key sources of high heavy metal concentrations in faecal sludge in the rainy season would enable sector stakeholders to take appropriate and corrective measures for pollution prevention.

- Key barriers and enablers of source separation systems: source separation is one way to achieve proper faecal sludge management in Phnom Penh and other cities in a comparable situation and could also improve the resource recovery potential. However, studies on key barriers and enablers in introducing source separation in Phnom Penh and other low- and middle-income settings are needed before introducing such systems, to ensure successful implementation.
- Prerequisites and sustainability criteria: the screening and sustainability criteria employed and the four treatment alternatives identified in this study could be applicable in other cities in low- and middle-income countries when planning faecal sludge management. However, additional studies on the transferability and applicability of the sustainability criteria are needed to strengthen the generalisability of the findings in different settings.
- Acceptability of reuse products: vermicomposting and BSFL composting scored highest for economic and environment criteria. They also give more value-added products, in addition to biosolids. However, there is no market information about larvae and worms locally. The market attractiveness of the reuse products should be studied before implementation of these treatment technologies in cities in low- and middle-income countries, including Phnom Penh. The performance of these two technologies when using feedstock with elevated concentrations of heavy metals should also be investigated.
- Risk assessment of reuse product: to safeguard public health, risk assessment of all reuse products from faecal sludge treatment technologies should be conducted before these are introduced onto the market.

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Popular science summary

Most urban residents in low- and middle-income countries use onsite sanitation systems. Unfortunately, the faecal sludge generated in these onsite sanitation systems poses management challenges along the entire service chain. Service coverage for emptying the sludge from household containment units and treatment plant capacity are often insufficient in many cities in low- and middle-income countries, resulting in indiscriminate disposal of faecal sludge in open environments. Therefore, proper faecal sludge management is needed to achieve United Nations SDG goal 6.2 by 2030. Resource recovery from faecal sludge could be a paradigm shift in proper faecal sludge management, while providing environmental protection and also minimising public health risks.

The aim of this thesis was to support faecal sludge management planning at citywide scale in low- and middle-income countries. The main focus was on resource recovery potential from faecal sludge in waterborne systems, using the specific case of Phnom Penh, Cambodia. The work involved determining qualities and quantities of faecal sludge and identifying challenges with current faecal sludge management practices, as well as appropriate treatment solutions. A range of methods were used in the work, including faecal sludge sampling and analysis, stakeholder interviews, and field observations. Multi-criteria assessment was performed to evaluate the different treatment options. The findings obtained provide important guidance in implementing proper faecal sludge management in Phnom Penh and possibly other cities in low- and middle-income countries where similar sanitation systems exist.

Qualities and quantities of faecal sludge generated in Phnom Penh were low compared with values reported in previous studies. Multiple factors contributed to low concentrations of nutrients in faecal sludge in Phnom Penh, including dilution from use of water flush toilets and addition of water during emptying events, use of containment units that capture mixed wastewater fractions, and having the onsite containment unit connected to the urban drainage network. The quantities of faecal sludge produced in Phnom Penh were low due to low emptying frequency at households, as no regular emptying is required and local residents empty their containment unit only when it is full or clogged.

Another problem is that concentrations of heavy metals (mercury and zinc) in the sludge exceeded the permissible limit set in the Cambodian standard for organic fertiliser and the Swedish standard for compost. Therefore, faecal sludge in Phnom Penh has limited reuse potential. Faecal sludge produced in other cities in low- and middle-income countries might have similar ranges of qualities and quantities, and might also contain elevated concentrations of heavy metals if similar onsite sanitation systems are used.

The main faecal sludge disposal sites in Phnom Penh are two nearby natural wetlands, which provide some purification before water reaches the final recipients (the Tonle Sap and Bassac rivers). This thesis showed that sludge emptying and transportation operators prefer to travel less than 9 km to disposal sites, to save travel costs and time. Sanitation stakeholders in Phnom Penh and in other cities in low- and middle-income countries should bear in mind transport distance when deciding on the location of any new centralised treatment plant or authorised disposal site. It is suspected that long transport distance from source to disposal site may lead to indiscriminate disposal of faecal sludge in the environment.

However, the resources present in faecal sludge in Phnom Penh can be recovered instead of being indiscriminately dumped in natural wetlands. Small quantities of total nitrogen (65 tons) and phosphorus (13 tons) could be recovered from faecal sludge in Phnom Penh, instead of discharging these into the two natural wetlands annually. Suggested alternatives to tackle the current challenges in faecal sludge management services are: (i) use of treated faecal sludge as a soil conditioner for public green spaces; (ii) upstream source control to prevent contamination of the sludge; and (iii) introducing source separation systems. Use of treated faecal sludge as a soil conditioner is a short-term solution that requires no/minimal change in infrastructure and might also have high public acceptance, as it is not related to food production for human consumption. Solar drying and vermicomposting would be appropriate to produce biosolids for use as a fertiliser for inedible plants, trees and grass.

Prevention of upstream pollution is a medium-term solution that requires more effort and collaboration between stakeholders, more time and some modification to existing sanitation infrastructures, but would provide cleaner feedstock. Therefore, it would increase resource recovery potential and provide a stronger economic incentive than the short-term solution. Of the four technology options assessed in this thesis (solar drying, co-composting BSFL composting, and vermicomposting), co-composting was found to be best in producing biosolids that meet the USEPA class A pathogen requirement.

Source separation systems are a long-term solution that would require major changes in sanitation infrastructure. Feasibility of implementation of this solution will depend on local context and local people. In addition, treatment options for each wastewater stream from source separation still need further investigation to optimise the resource recovery potential.

Selection of the best treatment option for faecal sludge management in any city will depend on scoring of sustainability criteria and trade-offs for sanitation stakeholders.

Overall, this thesis provided important data inputs that can help sector stakeholders tackle the current challenges in faecal sludge management in Phnom Penh. The findings can also be of relevance for planners in other cities in low- and middle-income countries with comparable sanitation systems.

Populärvetenskaplig sammanfattning

Majoriteten av människor i stadsområden i låg- och medelinkomstländer använder vanligtvis decentraliserade avloppssystem. Tyvärr blir slammet som genereras en utmaning att hantera för hela servicekedjan. Servicekedjan för tömning av slammet från slamavskiljarna och reningsverkskapacitet för att behandla slammet är ofta otillräcklig i de flesta städer i låg- och medelinkomstländer. Detta resulterar i okontrolerad hantering av slammet i miljön. Därför behövs korrekt slamhantering för att närma oss uthållighetmålet 6.2 till 2030. Resursåtervinning från avloppsslam kan vara ett nytt paradigmskifte för korrekt slamhantering. Det är inte bara för miljöskydd utan också för att minimera folkhälsoriskerna.

Denna avhandling syftade till att stödja planering av slamhantering från slamavskiljarna i stadsskala med fokus på vattenburna system. Huvudfokus låg också på resursåtervinningspotential från slammet, där Phnom Penh i Kambodja används som fallstudie. Arbetet innebar att fastställa kvalitet och kvantitet av slammet från enskilda avloppsanläggningar och identifiera utmaningar i nuvarande praxis för slamhantering, samt lämpliga behandlingstekniker. Denna studie använde olika metoder, inklusive provtagning och analys av fekalt slam, intervjuer med intressenter och fältobservationer. Multikriterieranalys gjordes för att utvärdera de olika behandlingsalternativen. Resultaten i denna avhandling ger vägledning för att förbättra korrekt slamhantering i Phnom Penh och möjligen andra städer i låg- och medelinkomstländer där liknande sanitetssystem finns.

Kvalitet och kvantitet av slammet som genereras i Phnom Penh ligger i ett lägre intervall jämfört med värden presenterade i tidigare studier från andra delar av världen. Flera orsaker till de låga kemiska egenskaperna slammet i Phnom Penh var användningen av vattentoaletter, tillsats av vatten under tanktömning, system som inte separerande olika avloppsvattenfraktioner, och anslutning till stadensavloppetnät. Mängden slam som produceras i Phnom Penh är också låg på grund av låg tömningsfrekvens i hushållen. Ingen regelbunden tömning krävs.

Lokalinvånare tömmer sina tankar eftersom de antingen är fulla eller har stopp. Dessutom är koncentrationen av två av de studerade tungmetallerna (kvicksilver och zink) högre än den tillåtna gränsen för kambodjansk standard för organisk gödsel och svenska gränsvärden för kompost. Därför har slammet i Phnom Penh begränsad återanvändningspotential. Slam som produceras i andra städer i låg- och medelinkomstländer kan ha liknande kvalitet och kvantitet, samt förhöjd koncentration av tungmetaller om liknande sanitetssystem används.

Två huvudsakliga våtmarker spelar nyckelroll som recipient för slam i Phnom Penh före de slutliga recipienterna (floderna Tonle sap och Bassac). Denna studie fann att tömnings- och transportoperatörer föredrar att resa mindre än nio km från källor till tömningsplats för vacuumbilens tank, främst för att spara resekostnader och tid. Detta ger en signal till avloppsplanerare i Phnom Penh såväl som i andra städer i låg- och medelinkomstländer när de planerar för centraliserade reningsverk och dess placering. Dessutom verkar längre sträckor från källor till centraliserat reningsverk kunna leda till okontrollerad hantering av slammet.

Det finns dock resurser att utvinna från slam istället för att urskillningslöst deponeras i naturliga våtmarker. Små mängder, i förhållande till den lokala gödselanvändningen, totalt kväve (65 ton) och fosfor (13 ton) kunde dock återvinnas från slam i Phnom Penh, istället för att som idag släppa ut det till de två våtmarkerna. Tre alternativ för att ta itu med nuvarande utmaningar inom slamhantering som föreslås är: i) Användning av behandlat fekalt slam som jordförbättrare i offentliga grönområden; ii) Uppströms förebyggande av föroreningar; och iii) införa källsorterande avloppssystem. Implementering av en kortsiktig lösning för slamhantering, som alternativ ett, kräver liten förändring av nuvarande infrastruktur. Behandlat slam som ska användas som jordförbättrare kan också ha hög allmän acceptans enligt erfarenhet från andra städer. Enkel reningsteknik som soltorkning skulle räcka för att producera en jordförbättrare för användning till växter, träd och gräs som inte konsumeras.

En lösning på medellång sikt som förebyggande av föroreningar uppströms kräver mer ansträngning och samarbete mellan alla berörda parter. Detta alternativ kräver mer tid och kräver vissa ändringar i befintliga avloppsinfrastrukturen i staden men skulle ge renare slamråvara. Därför skulle det ge mer ekonomiska incitament för återföring än den kortsiktiga lösningen. Slam som produceras efter implementering av detta alternativ har högre återanvändningspotential än nuvarande slam. I denna lösning på medellång sikt rankades samkomostering av slam och matavfall först bland de fyra utvärderade behandlingsteknologialternativen. Övriga behandlingar som utvärderades var soltorkning, BSFL-kompostering och vermikompostering för att producera gödsel/jordförbättrare som uppfyller USEPA klass A hygienkrav.

För en långsiktig lösning kräver källsorterande system som medför stora förändringar i sanitetsinfrastrukturen. Möjligheten att implementera detta alternativ beror på lokal kontext och människor. Reningsalternativ för varje avloppsvattenström från källsortering behöver undersökas ytterligare för att optimera dess återanvändningspotential, men slutprodukten förväntas vara både av större kvantitet och kvalitet.

Valet av alternativ för hantering av fekalt slam i alla städer beror på poängsättning av hållbarhetskriterier och avvägningar som sanitetsintressenter tar hänsyn till.

Sammantaget har den här avhandlingen bidraget med viktiga input för beslutsfattare och planerar i sanitetssektors för att tackla de nuvarande utmaningarna inom slamhantering i Phnom Penh. Dessa insatser kan också vara relevanta för andra städer i låg- och medelinkomstländer, som har jämförbara sanitetssystem.

មូលន័យសង្ខេប

ប្រជាជនភាគច្រើន នៅតាមតំបន់ទីក្រុងនៃបណ្តាប្រទេសដែលមានប្រាក់ចំណូលទាបនិងមធ្យម ប្រើប្រាស់ប្រព័ន្ធអនាម័យនៅនឹងកន្លែង។ ការគ្រប់គ្រងភក់លាមកដែលបញ្ចេញពីប្រព័ន្ធអនាម័យនៅនឹងកន្លែង គឺជាបញ្ហាប្រឈមក្នុងការគ្រប់គ្រងខ្សែចង្វាក់អនាម័យទាំងមូល។ អត្រាគ្របដណ្តប់នៃសេវាកម្មបូមភក់លាមកពីអាងស្តុក និងសមត្ថភាពរបស់រោងចក្រប្រព្រឹត្តកម្មនៅក្នុងតំបន់ទីក្រុងនៃបណ្តាប្រទេសទាំងនោះមិនទាន់គ្រប់គ្រាន់ ដែលបណ្តាលឲ្យមានការចាក់ភក់លាមកចោលពាសវាលពាសកាលនៅក្នុងបរិស្ថាន។ ដូចនេះ ការគ្រប់គ្រងភក់លាមកឲ្យបានត្រឹមត្រូវគឺជាតម្រូវការចាំបាច់ដើម្បីសម្រេចបានគោលដៅអភិវឌ្ឍន៍ដោយចីរភាព ៦.២ របស់អង្គការសហប្រជាជាតិ នៅឆ្នាំ២០៣០។ ការទាញយកធនធានពីភក់លាមកអាចជាការផ្លាស់ប្តូរយ៉ាងសំខាន់មួយក្នុងការគ្រប់គ្រងភក់លាមកឲ្យបានត្រឹមត្រូវ ហើយក៏អាចគាំពារបរិស្ថាន និងកាត់បន្ថយហានិភ័យដល់សុខភាពសាធារណៈ។

គោលបំណងនៃនិក្ខេបបទនេះ គឺដើម្បីគាំទ្រដល់ការរៀបចំផែនការគ្រប់គ្រងភក់លាមកនៅក្នុងតំបន់ទីក្រុងនៃបណ្តាប្រទេសដែលមានប្រាក់ចំណូលទាប និងមធ្យម។ គោលបំណងចំបងគឺផ្តោតលើសក្តានុពលនៃការទាញយកធនធានពីភក់លាមក ពីប្រព័ន្ធអនាម័យនៅនឹងកន្លែងដែលប្រើប្រាស់ទឹក ដោយជ្រើសរើសរាជធានីភ្នំពេញ នៃព្រះរាជាណាចក្រកម្ពុជាជាករណីសិក្សា។ ការស្រាវជ្រាវនេះរួមមាន ការវិភាគគុណភាព និងការកំណត់បរិមាណភក់លាមក និងកំណត់ពីបញ្ហាប្រឈមក្នុងការគ្រប់គ្រងភក់លាមកនាពេលបច្ចុប្បន្ន ក៏ដូចជាដំណោះស្រាយសមស្របក្នុងការធ្វើប្រព្រឹត្តកម្ម។ ការស្រាវជ្រាវនេះបានប្រើប្រាស់វិធីសាស្ត្ររួមមាន ការប្រមូលសំណាកភក់លាមក និងការវិភាគ សម្ភាសន៍ក្រុមអ្នកពាក់ព័ន្ធ និងការអង្កេតនៅទីវាល។ ការសិក្សានេះក៏បានប្រើប្រាស់ការវាយតម្លៃពហុលក្ខណវិនិច្ឆ័យ ដើម្បីថ្លឹងថ្លែងនូវជម្រើសប្រព្រឹត្តកម្មនានា។ លទ្ធផលនៃការសិក្សានេះ គឺជាធាតុចូលយ៉ាងសំខាន់សម្រាប់ត្រួសត្រាយដល់ការ

គ្រប់គ្រងភក់លាមកនៅរាជធានីភ្នំពេញ និងបណ្ដាទីក្រុងនៃប្រទេសកំពុងដែលមានប្រាក់ចំណូលទាប និងមធ្យម ដែលមានប្រព័ន្ធអនាម័យស្រដៀងនឹងរាជធានីភ្នំពេញ។

លទ្ធផលបង្ហាញថាទាំងគុណភាព និងបរិមាណភក់លាមកដែលបញ្ចេញនៅ រាជធានីភ្នំពេញ មានកម្រិតទាប បើប្រៀបធៀបទៅនឹងការសិក្សាដទៃទៀត។ នៅរាជធានីភ្នំពេញ ភក់លាមកមានកម្រិតសារធាតុចិញ្ចឹមទាបអាចអាស្រ័យដោយកត្តាជាច្រើនដូចជា ប្រភេទបង្គន់ដែលប្រើប្រាស់ទឹក ការបាញ់ទឹកក្នុងកំឡុងពេលបូមភក់លាមកពីអាងស្តុក ការបង្ហូរសំណល់រាវគ្រប់ប្រភេទចូលអាងស្តុកតែមួយ និងអាងស្តុកដែលភ្ជាប់ទៅនឹងបណ្តាញលូទីក្រុង។ ភក់លាមកដែលបញ្ចេញក៏មានបរិមាណតិចអាស្រ័យដោយ ភាពញឹកញាប់នៃតម្រូវការបូមចេញពីអាងស្តុកនៅតាមផ្ទះ។ នៅរាជធានីភ្នំពេញមិនតម្រូវឲ្យមានការបូមភក់លាមកឲ្យបានទៀងទាត់នោះទេ ហើយប្រជាជនបូមភក់លាមកពីអាងស្តុកតែនៅពេលដែលអាងស្តុកពេញ ឬក៏ស្ទះតែប៉ុណ្ណោះ។

ការសិក្សានេះក៏បានបង្ហាញថា ភក់លាមកក៏ផ្ទុកលោហៈធ្ងន់ខ្ពស់ (បារត និងសង្ក័សី) ដែលលើសពីកម្រិតអនុញ្ញាតិនៅក្នុងបទដ្ឋានជីសរីរាង្គនៅប្រទេសកម្ពុជា និងបទដ្ឋានជីកំប៉ុស្ត៍ប្រទេសស៊ុយអែត។ ដូចនេះ ភក់លាមកនៅរាជធានីភ្នំពេញមានសក្តានុពលប្រើប្រាស់ឡើងវិញទាប។ ភក់លាមកដែលបញ្ចេញនៅបណ្ដាទីក្រុង នៃប្រទេសដែលមានប្រាក់ចំណូលទាប និងមធ្យម ប្រហែលជាអាចមានគុណភាព និងបរិមាណ និងកម្រិតលោហៈធ្ងន់ខ្ពស់ ប្រសិនបើទីក្រុងនៃប្រទេសទាំងនោះប្រើប្រាស់ប្រព័ន្ធអនាម័យនៅនឹងកន្លែងស្រដៀងនឹងរាជធានីភ្នំពេញ។

កន្លែងចាក់ចោលភក់លាមកនៅរាជធានីភ្នំពេញ គឺស្ថិតនៅតំបន់ដីសើមធម្មជាតិពីរ ដែលអាចសម្អាតភក់លាមកខ្លះមុនពេលបង្ហូរចូលទៅក្នុងទន្លេសាប និងទន្លេបាសាក់។ និក្ខេបបទនេះក៏បានរកឃើញថា ប្រតិបត្តិករបូមភក់លាមកភាគច្រើននិយមធ្វើដំណើរតែក្នុងចម្ងាយជាមធ្យម ៩ គីឡូម៉ែត ដើម្បីចាក់ភក់លាមកចោល ក្នុងគោលបំណងសន្សំសំចៃការចំណាយ និងពេលវេលា។ អ្នកពាក់ព័ន្ធក្នុងវិស័យអនាម័យក្នុងរាជធានីភ្នំពេញ និងទីក្រុងនានានៃប្រទេសដែលមានប្រាក់ចំណូលទាប និងមធ្យម គួរតែគិតពីចម្ងាយនៃការធ្វើដំណើរនៅពេលដែលសម្រេចចិត្តក្នុងការជ្រើសរើសទីតាំងរោងចក្រប្រព្រឹត្តកម្ម ឬទីតាំងចាក់ចោលថ្មី។ ការធ្វើដំណើរទៅទីតាំងចាក់ចោលដែលមានចម្ងាយឆ្ងាយ អាចជាមូលហេតុដែលនាំឲ្យមានការចាក់ភក់លាមកពាសវាលពាសកាលនៅក្នុងបរិស្ថាន។

សារធាតុចិញ្ចឹមក្នុងភក់លាមកនៅរាជធានីភ្នំពេញអាចទាញយកមកប្រើប្រាស់ជំនួសឲ្យការចាក់ចោលក្នុងតំបន់ដីសើមធម្មជាតិ។ បរិមាណអាសូតប្រមាណ ៦៥តោន និងផូស្វ័រប្រមាណ ១៣តោន អាចទាញយកពីភក់លាមកប្រចាំឆ្នាំ។ ជម្រើសក្នុងការដោះស្រាយបញ្ហាប្រឈមក្នុងសេវាកម្មគ្រប់គ្រងសំណល់ភក់លាមក មានដូចជា៖ (i) ការប្រើប្រាស់ជីភក់លាមកសម្រាប់ទ្រទ្រង់គុណភាពដីនៅតាមសួនច្បារសាធារណៈ (ii) ការការពារការបំពុលពីប្រភព និង (iii)

ការប្រើប្រាស់ប្រព័ន្ធអនាម័យញែកនៅនឹងប្រភព។ ការប្រើប្រាស់ដីភក់លាមកសម្រាប់ទ្រទ្រង់គុណភាពដីសម្រាប់ដំណោះស្រាយរយៈពេលខ្លី មិនតម្រូវឲ្យកែប្រែហេដ្ឋារចនាសម្ព័ន្ធអនាម័យ និងអាចទទួលបានការទទួលយកពីសាធារណជន ហើយវាមិនពាក់ព័ន្ធនឹងផលិតកម្មម្ហូបអាហារសម្រាប់មនុស្សប្រើប្រាស់ផងដែរ។

ការការពារការបំពុលពីប្រភព គឺជាដំណោះស្រាយរយៈពេលមធ្យមដែលតម្រូវឲ្យមានកិច្ចខិតខំប្រឹងប្រែង និងសហការណ៍គ្នារវាងអ្នកពាក់ព័ន្ធ ត្រូវការពេលវេលា និងការកែប្រែហេដ្ឋារចនាសម្ព័ន្ធអនាម័យដែលមានស្រាប់ ប៉ុន្តែអាចផ្តល់នូវភក់លាមកដែលគ្មានការបំពុលពីលោហៈធ្ងន់។ ដូចនេះ ការការពារការបំពុលពីប្រភពអាចបង្កើនសក្តានុពលនៃការទាញយកធនធាន និងអាចផ្តល់នូវផលចំណេញផ្នែកសេដ្ឋកិច្ចច្រើនជាងជម្រើសរយៈពេលខ្លី។ ការផលិតដីកំប៉ុស្តិ៍ដោយការលាយភក់លាមក និងសំណល់សរីរាង្គអាចផលិតបានដីកំប៉ុស្តិ៍កម្រិត A ដែលគ្មានសារពាង្គកាយបង្ករោគ ស្របទៅតាមគោលការណ៍ណែនាំរបស់ USEPA ដែលជាជម្រើសដែលប្រសើរជាងគេ នៅក្នុងចំណោមជម្រើសបច្ចេកវិទ្យាទាំងបួន (បច្ចេកវិទ្យាសម្ងួតដោយពន្លឺព្រះអាទិត្យ ការផលិតដីកំប៉ុស្តិ៍ដោយការលាយភក់លាមក និងសំណល់សរីរាង្គ ការផលិតដីកំប៉ុស្តិ៍ដោយសត្វល្អិត និងការផលិតដីកំប៉ុស្តិ៍ដោយជន្លេន)។

ការប្រើប្រាស់ប្រព័ន្ធអនាម័យញែកនៅនឹងប្រភព គឺជាដំណោះស្រាយរយៈពេលវែង ដែលតម្រូវឲ្យកែប្រែហេដ្ឋារចនាសម្ព័ន្ធអនាម័យស្ទើរតែទាំងស្រុង។ ការអនុវត្តជម្រើសនេះអាស្រ័យលើប្រជាជន និងស្ថានភាពនៃទីក្រុងនីមួយៗ។ លើសពីនេះទៅទៀត ជម្រើសប្រព្រឹត្តកម្មសម្រាប់ប្រភេទសំណល់នីមួយៗត្រូវសិក្សាបន្ថែម ដើម្បីបង្កើនសក្តានុពលនៃការទាញយកធនធានមកប្រើប្រាស់ឡើងវិញ។

ការជ្រើសរើសជម្រើសដែលប្រសើរបំផុតសម្រាប់ការគ្រប់គ្រងភក់លាមកនៅក្នុងទីក្រុងមួយអាស្រ័យលើលក្ខណវិនិច្ឆ័យចីរភាព និងការថ្លឹងថ្លែងរបស់អ្នកពាក់ព័ន្ធផ្នែកអនាម័យ។

ជារួម និក្ខេបបទនេះបានផ្តល់នូវធាតុចូលយ៉ាងសំខាន់ ដែលអាចជួយឲ្យអ្នកពាក់ព័ន្ធផ្នែកអនាម័យដោះស្រាយបញ្ហាប្រឈម ក្នុងការគ្រប់គ្រងភក់លាមកក្នុងរាជធានីភ្នំពេញនាពេលបច្ចុប្បន្ន។ លទ្ធផលនេះ ក៏អាចជាធាតុចូលយ៉ាងសំខាន់ដល់អ្នកធ្វើផែនការផ្នែកអនាម័យនៅទីក្រុងនានាក្នុងប្រទេសដែលមានប្រាក់ចំណូលទាប និងមធ្យមផ្សេងទៀត ដែលមានប្រព័ន្ធអនាម័យស្រដៀងនឹងប្រព័ន្ធអនាម័យនៅរាជធានីភ្នំពេញ។

Acknowledgements

The work presented in this thesis would have not been accomplished without financial support from the Swedish International Development Cooperation Agency through "Sweden-Royal University of Phnom Penh Bilateral program" [Contribution Number: 11599], the Swedish University of Agricultural Sciences (SLU), International Science Program (ISP), and the Royal University of Phnom Penh (RUPP).

My sincere gratitude to my supervisor group: Björn Vinnerås, Jennifer McConville, Christian Zurbrügg, Thammarat Koottatep and Kok Sothea, for their tireless support, constant constructive feedback, motivation and encouragement throughout the entire journey. My main supervisor, Björn, thanks for the inspiration in plant nutrient recycling from waste streams and all the incredible comments to bring my research to this point. Jennifer, thanks for thoroughly reading my drafts, quick response despite your tight schedule and inspiring me in system analysis of nutrient recycling.

My thanks to past and present members of the Kretsloppsteknik group. Håkan: for your impressive presentation back in 2017 during my first visit to SLU–it was the reason I joined the group. Annika, Cecilia and Prithvi: for good discussions, guidance and sharing knowledge in specific topics. Viki: for friendship and warm welcome since my first year. Susbo potluck party crews and Cambodians in Uppsala: for friendship, shopping and fun times.

Thanks to all my colleagues at the Department of Energy and Technology. I am grateful to Claudia for her statistical support. My special thanks to all stakeholders for their valuable time, for sharing their insights and knowledge. Thanks also to students and pit emptying and transportation operators for their assistance and participation during data collection for this thesis.

To my family, thanks for being there in both the good and the bad times. My husband, thanks for being an excellent father to our kids, taking care of them in the best possible way, loving and caring. You walked this journey with me. I proudly say you are my superhero!

Journal of
Water, Sanitation & Hygiene for Development

Journal of Water, Sanitation and Hygiene for Development Vol 12 No 1, 129 doi: 10.2166/washdev.2021.193

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).

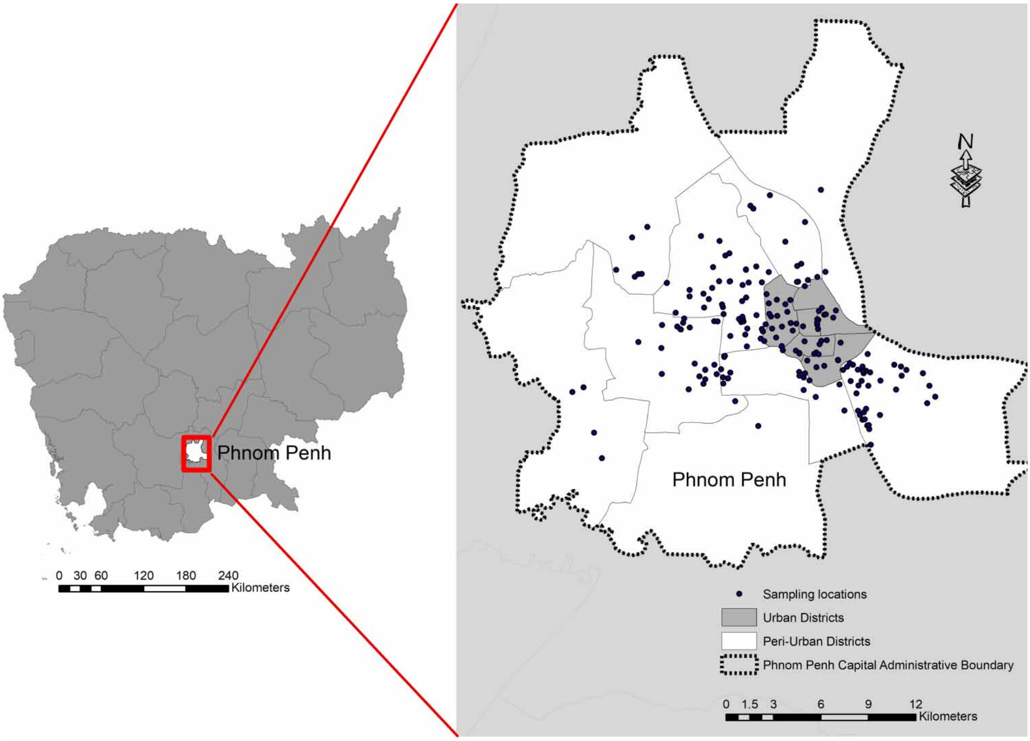

Figure 2 | The study area map of the city Phnom Penh and sampling locations of the 194 samples, where demographic, environment, and technical data were collected during sampling.

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

	Summary statistics from this study							**Mean value from other studies**					
Parameter	**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.

ACKNOWLEDGEMENTS

The Swedish International Development Agency fully supported this study through the 'Sweden-Royal University of Phnom Penh Bilateral program' (Contribution No. 11599). The authors thank Claudia von Brömssen for her statistical advice. This work would not have been accomplished without assistance from Phon VuochKeang, Chin Sonita, Som Sodalik, Norn Sakneka, Sovanna Phina, and Pao Seangly in field work and sample analysis.

DATA AVAILABILITY STATEMENT

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

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First received 7 October 2021; accepted in revised form 23 November 2021. Available online 7 December 2021

Journal of
Water, Sanitation & Hygiene for Development

Journal of Water, Sanitation and Hygiene for Development Vol 13 No 7, 527 doi: 10.2166/washdev.2023.101

Corrigendum: *Journal of Water, Sanitation and Hygiene for Development* 1 January 2022; 12 (1): 129–140: Factors influencing physicochemical characteristics of faecal sludge in Phnom Penh, Cambodia, Chea Eliyan, Björn Vinnerås, Christian Zurbrügg, Thammarat Koottatep, Kok Sothea, Jennifer McConville

https://doi.org/10.2166/washdev.2021.193

The authors regret that there was an analytical error for total nitrogen (TN) concentration in our samples, leading to lower detection and reported values of TN concentration in our paper. We believe these lower reported values (Tables 1 and 2 and Supplementary Table S1) in our paper are not valid.

Based on our recent study of faecal sludge qualities in Phnom Penh, TN ranged between 1,500-3,300 mg/l. We have realized that lower detection of TN concentration in this paper is most probably related to analytical error with the Hach range standard test (LCK 338) method used. The high COD in the faecal sludge samples was an interference and the oxidation reagents added were not enough to transform all organic and inorganic nitrogen into nitrate in the digestion process, for this reason the compound measured as total nitrogen when using this specific method. To obtain a more accurate analysis, using Spectroquant Crack set (Cat. No. 1.14963) digestion method, more oxidants need to be used and/or a higher dilution rate of the samples.

The authors would like to apologise for any inconvenience caused.

Supporting information for

Factors Influencing Physicochemical Characteristics of Faecal Sludge in Phnom Penh, Cambodia

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Contents of this file

Questionnaire used to collect demographic, environment and technical data of the containment from users and emptiers (Questionnaire for household survey and checklist of with pit emptiers).

Table S1| Summary statistics on sludge qualities from septic tanks and cesspits. For abbreviations, see text

Figure S1| Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN, BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with respect to septic tank and cesspit containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S2| Boxplots of parameters studied (BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with respect to lined and unlined containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S3| | Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN) in faecal sludge in Phnom Penh with respect to lined and unlined containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S4| Boxplots of parameters studied (PO_4-P, NH_4-N, BOD, TS, VSS) in faecal sludge in Phnom Penh with regard to connection (or not) to the urban drainage network. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S5| Boxplots of parameters studied (TP, TN) in faecal sludge in Phnom Penh with respect to connection (or not) to the urban drainage network. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S6| Boxplots of parameters studied (PO_4-P, NH_4-N, TN) in faecal sludge in Phnom Penh with regard to addition of water during septic tank/cesspit emptying. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S7| Boxplots of parameters studied (TP, BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with regard to addition of water during septic tank/cesspit emptying. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S8| Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN, BOD) in faecal sludge in Phnom Penh with regard to type of wastewater collected in containment units (blackwater only or a mixture of wastewaters). Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S9| Boxplots of parameters studied (TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with regard to type of wastewater collected in containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S10| Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN, BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with respect to of users of the containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Figure S11| Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN, BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with respect to the age of the containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

Consent Form

Resource Recovery for Sustainable Sanitation Management in Phnom Penh, Cambodia

Greeting! My name is **Chea Eliyan**, a PhD student at Swedish University of Agricultural Sciences. I am conducting my PhD research on "Resource Recycling for Sustainable Sanitation Management in Phnom Penh, Cambodia". The overall aim of the study is to identify the opportunities for safe nutrients recovery from household onsite sanitation faecal sludge, which is currently being disposed of into the environment without any treatment. This survey is part of my research to draw the baseline on households faecal sludge characteristics in Phnom Penh, to identify the environmental risk from the current faecal sludge management practices, and the potential to transfer this current system to the more circular one. Your house has been randomly selected and I would like you to participate in my study, if you decide to agree. We would ask you some questions on your households, its members and characteristics and on sanitation aspects which focus on faecal sludge, of your household. We will also take a faecal sludge sample that will be emptied by E & T service provider from your containment. The sample will be tested for physical and chemical properties at our laboratory of Department of Environmental Science, Royal University of Phnom Penh. The sample analysis will be made anonymous and the data interpretation will also be generalized as the city wide scale. Thus, the result from this study will has no any linkage back to you. The interview could approximately last for 25-30 minutes. Your participation is absolutely voluntary and you can withdraw from the survey at any time, you won't be penalized or lose any benefits for which you otherwise qualify. You may also choose not to answer any questions. You will not have to pay to participate in this survey; nor will we pay you. The information you will be providing us will be confidential and only the researchers who are involved in this study will have access to it. Your data will also be stored without your name or any other kind of link that would enable us to identify what data is yours. Therefore, it will be available for use in future research studies forever and cannot be removed.

If you have any questions about this research study itself, please contact: Chea Eliyan, +855-17 485 675. If you feel that you have been harmed in any way by your participation in this study, please contact: Björn Vinnerås, + 46 705 521 521 or Jennifer McConville, +46 76 783 7084.

This consent form is not a contract. It is a written explanation of what will happen during the study if you decide to participate. You are not waiving any legal rights by agreeing to participate in this study.

Could we start the interview?	☐ (1) Yes ☐ (2) No

☐ I am between 18 and 70 years old (if not, the person is not eligible to respond)

______________________________ ________________________

Respondent signature Date

Questionnaire for household survey

Resource Recovery for Sustainable Sanitation Management in Phnom Penh, Cambodia

Part A: Registration

A.1 Interviewer info	Name:	Signature:
A.2 Verified by	Name:	Signature:
A.3 Interview date and start time	A.3.1 Date:	A.3.2 Time:
A.4 District		
A.5 Commune		
A.6 Village		
A.7 GPS coordinate	A.7.1 X:	A.7.2 Y:
A.8 GPS ID		
A.9 ID code		
A.10 FS ID		

Part B: General information on the household

B.1 Respondent's profile

B.1.1 Record respondent sex

☐ (1) Male
☐ (2) Female

B.1.2 Total number of family members, including respondent

[insert number]:……………………………person(s)

B.1.3 Age of respondent and family members [insert number]

☐ (1) Less than 3 years old:…………………….person(s)
☐ (2) More than 3 years old:…………………… person(s)

ID	B.1.4 What is the highest education of each member in your family? (0) No formal education completed (1) Primary (grade 1-6) (2) Secondary (grade 7-9) (3) High school (grade 10-12) (4) Undergraduate (bachelor education) (6) Graduate (master education) (7) Others (specify)…………….	B.1.5 What is the primary occupation of each member? (*Record the position and institution of individual)* (1) Government (2) Private sector (3) NGOs (4) DPs (5) Others (specify)	B.1.6 What is the secondary occupation of each member? (*Record the position and institution of individual)* (1) Government (2) Private sector (3) NGOs (4) DPs (5) Others (specify)
R			

B.1.7 Are you a main income generator in your family?

☐ (1) Yes (If Yes, go to B.1.9)
☐ (2) No

B.1.8 What is the occupation of the main income generator?

☐ (1) Government
☐ (2) Private sector
☐ (3) NGOs
☐ (4) DPs
☐ (5) Others (specify)

B.1.9 Total number of family members who permanently stay at home (record the number of those who have no job outside home based on B.1.5

☐ (1) Kid (Less than 3 year old):……………………person(s)
☐ (2) Adult (More than 3 year old:……………………person(s)

B.2 Household socio-economic

B.2.1	What kind of building does the household occupy? *(Record observation)*	☐ (1) Flat (single-storey) ☐ (2) Flat (multi-storey) ☐ (3) Simple house in a plot of land ☐ (4) Villa ☐ (6) Other (specify)……………………		
B.2.2	What is the number of room occupied by your family? (Exclude kitchen, bathroom, toilet and storeroom)	[insert the number] …………………………rooms		
B.2.3	What is the size of your land? *[insert number in square meter]*	……………………….m^2		
B.2.4	Is this house/residence owned or rented by a member of the household?	☐ (1) Owned and nothing to pay ☐ (2) Owned and have to pay to bank ☐ (3) Rented ☐ (4) Others (Specify) ………………….		
B.2.5	How long have you/ members of your household been living on this location/plot?	Enter the complete years and months ……………………......		
B.2.6	When was this house built? (Record the year that the house was completely built, or approximate the age of the building and fill NA if they don't know.	Enter the complete years or age of the building ……………………......		
B.2.7	Does your household have the following?	Item	Tick that apply	Record number
		(1) Cell phone	☐ (1) Yes ☐ (2) No	
		(2) Television	☐ (1) Yes ☐ (2) No	
		(3) Refrigerator	☐ (1) Yes ☐ (2) No	
		(4) Washing machine	☐ (1) Yes ☐ (2) No	
		(5) Air conditioner	☐ (1) Yes ☐ (2) No	
		(6) Bike	☐ (1) Yes ☐ (2) No	
		(7) Motorbike	☐ (1) Yes ☐ (2) No	
		(8) Car	☐ (1) Yes ☐ (2) No	
		(9) Computer (personal and desktop)	☐ (1) Yes ☐ (2) No	

		(10) Fan	☐ (1) Yes ☐ (2) No	
B.2.8	What is the main material of the roof? *(Record observation)*	☐ (1) Thatch/ Bamboo/Grass ☐ (2) Tile ☐ (3) Wood/plywood ☐ (4) Concrete/Brick/Stone ☐ (5) Galvanized iron/Aluminum/Other metal sheets ☐ (6) Asbestos cement sheet ☐ (7) Plastic/Synthetic material sheets ☐ (8) Others (Specify)		
B.2.9	What is the main material of the walls? *(Record observation)*	☐ (1) Thatch/Bamboo/Grass/Reeds ☐ (2) Tile ☐ (3) Wood/Plywood ☐ (4) Concrete/Brick/Stone ☐ (5) Galvanized iron/Aluminum/Other metal sheets ☐ (6) Asbestos cement sheet ☐ (7) Salvaged/improvised material ☐ (8) Others (Specify)		

B.3 About water use at household

B.3.1 What is your source of water supply and drinking water source?
(Interviewer should first tick the boxes for each source that is used. Then after that, ask the respondent which one they use the most, next most, and next most…to complete the ranking)

Source of water supply	**Rank**	**Drinking water source**	**Rank**
☐ (1) Piped into dwelling	➔	☐ (1) Piped into dwelling	➔
☐ (2) Piped to yard/plot	➔	☐ (2) Piped to yard/plot	➔
☐ (3) Public tap/ standpipe	➔	☐ (3) Public tap/ standpipe	➔
☐ (4) Tube well/ borehole	➔	☐ (4) Tube well/ borehole	➔
☐ (5) Protected dug well	➔	☐ (5) Protected dug well	➔
☐ (6) Unprotected dug well	➔	☐ (6) Unprotected dug well	➔
☐ (7) Protected spring	➔	☐ (7) Protected spring	➔
☐ (8) Unprotected spring	➔	☐ (8) Unprotected spring	➔
☐ (9) Rainwater	➔	☐ (9) Rainwater	➔
☐ (10) Bottled water /gallon container and dispenser	➔	☐ (10) Bottled water /gallon container and dispenser	➔
☐ (11) Refilled bottled water	➔	☐ (11) Refilled bottled water	➔
☐ (12) Cart with small tank/ drum	➔	☐ (12) Cart with small tank/ drum	➔
☐ (13) Tanker-truck	➔	☐ (13) Tanker-truck	➔
☐ (14) Surface Water (river, dam, lake, pond, stream, canal, irrigation channels)	➔	☐ (14) Surface Water (river, dam, lake, pond, stream, canal, irrigation channels)	➔
☐ (15) Others (specify)	➔	☐ (15) Others (specify)	➔

B.3.2 How much do you pay on average for water (both drinking and general use) per month?

[insert number in Riels]…………………………………………………………………………....

……………………………………………………………………………………………………....

……………………………………………………………………………………………………....

……………………………………………………………………………………………………....

B.3.3 How would you rate the cost of the water for your household? *(It is based on the reaction of the respondent during the interview and tick the box where appropriate)*

☐ (1) Very cheap
☐ (2) Inexpensive (at the affordable rate)
☐ (3) Expensive
☐ (4) Very expensive
☐ (5) Don't know/ No comment

B.3.4 What is the average quantity of water do you use per month? *[ask for water invoice from previous months if piped water source, otherwise some calculation may be needed]*

[insert number in cubic meter]……………………………………………………………………....

……………………………………………………………………………………………………....

……………………………………………………………………………………………………....

……………………………………………………………………………………………………....

Part C: Sanitation technology

C.1 About toilet (user interface)

C.1.1 How many toilet does your household own?

☐ (1) One
☐ (2) Two
☐ (3) Three
☐ (4) Four
☐ (5) Five
☐ (6) More than 5 (specify)………………………

C.1.2 What kind of toilet facility do members of your household usually use? (Multiple answers are possible) *[Record observation or ask question where applicable] (Enumerator use the printed pictures about the type of toilet to show householder to add visualization and get more accurate answers)*

Number of toilets	*Types of toilet*
………………………	☐ (1) Automatic cistern Flush
………………………	☐ (2) Pour/manual flush
………………………	☐ (3) Ventilated improved pit latrine
………………………	☐ (4) Pit latrine with slab
………………………	☐ (5) Pit latrine without slab/open pit
………………………	☐ (6) Composting toilet
………………………	☐ (7) Bucket
………………………	☐ (8) Hanging toilet
………………………	☐ (9) Others (specify)……………………..

C.1.3 Do you share any of these toilets with other households?

☐ 1. Yes
☐ 2. No (If NO go to C.1.6)

C.1.4 How many other **households** share this toilet?

☐ [insert number of households]…………………household(s)
☐ Don't Know

C.1.5 How many other **persons** (in that households) share this toilet?
☐ [insert number of persons]…………………………person(s)
☐ Don't Know

C.1.6 When these toilets were built? *Multiple answers are possible according to the number of toilet they might have (refer to C.1.1 and C.1.2)*

[insert number of years and months]……………………………………………………

……………………………………………………………………………………………..

……………………………………………………………………………………………..

……………………………………………………………………………………………..

C.1.7 Do you have access to toilet inside the house?
☐ (1) Yes
☐ (2) No

C.1.8 Do you use water for cleaning after using the toilet?
☐ (1) Yes
☐ (2) No

C.1.9 Do you use tissue paper for cleaning after using the toilet?
☐ (3) Yes
☐ (4) No

C.1.9 Are there any other materials (excluding water and tissue paper) do you use for cleaning after using the toilet?
☐ (3) Yes (specify)………………………………
☐ (4) No

C.2 About the containment (This section is designed to seek for detailed information about the containment that is being emptied during that emptying event. No matter how many containments the household has, please refer to the one that is being emptied)

C.2.1 Where are the contents of the toilet discharged?
(Enumerator use the printed pictures about the type of containments to show householder to add visualization and get more accurate answers)
☐ (1) One or more unlined circular cesspit connected to drainage facilities
☐ (2) One or more lined circular cesspit connected to drainage facilities
☐ (3) One or more unlined circular cesspit NOT connected to drainage facilities
☐ (4) One or more lined circular cesspit NOT connected to drainage facilities
☐ (5) Unlined rectangular cesspit connected to drainage facilities
☐ (6) Lined rectangular cesspit connected to drainage facilities
☐ (7) Unlined rectangular cesspit NOT connected to drainage facilities
☐ (8) Lined rectangular cesspit NOT connected to drainage facilities
☐ (9) Two or three chambers septic tank connected to drainage facilities
☐ (10) Two or three chambers septic tank connected to drainage facilities
☐ (11) Others (specify)…………………………………
☐ (12) Don't know

C.2.2 When was this containment built? *(This is referred to the containment that was connected to toilet and being emptied)*

[insert number of years and months]…………………………

C.2.3 Do you dispose of wastewater from kitchen, bathing and/or laundry to the same containment as toilet? *(This is to clarify if the wastewater goes to same containment as the above-mentioned toilet. Do not explain the purpose but simply ask and tick the respondent's answer).*

☐ (1) Yes, they all go to the same containment (Go to C.2.6)
☐ (2) Yes, wastewater from kitchen goes to the same containment as toilet (Go to C.2.5)
☐ (3) Yes, Wastewater from bathing and laundry go to the same containment as toilet (Go to C.2.4)
☐ (4) No, they all have separated containment (Go to C.2.4)

C.2.4 Where do you dispose of wastewater from kitchen?

☐ (1) One or more unlined circular cesspit connected to drainage facilities
☐ (2) One or more lined circular cesspit connected to drainage facilities
☐ (3) One or more unlined circular cesspit NOT connected to drainage facilities
☐ (4) One or more lined circular cesspit NOT connected to drainage facilities
☐ (5) Unlined rectangular cesspit connected to drainage facilities
☐ (6) Lined rectangular cesspit connected to drainage facilities
☐ (7) Unlined rectangular cesspit NOT connected to drainage facilities
☐ (8) Lined rectangular cesspit NOT connected to drainage facilities
☐ (9) Two or three chambers septic tank connected to drainage facilities
☐ (10) Two or three chambers septic tank connected to drainage facilities
☐ (11) Others (specify)…………………………………
☐ (12) Don't know

C.2.5 Where do you dispose of wastewater from bathing and laundry?

☐ (1) One or more unlined circular cesspit connected to drainage facilities
☐ (2) One or more lined circular cesspit connected to drainage facilities
☐ (3) One or more unlined circular cesspit NOT connected to drainage facilities
☐ (4) One or more lined circular cesspit NOT connected to drainage facilities
☐ (5) Unlined rectangular cesspit connected to drainage facilities
☐ (6) Lined rectangular cesspit connected to drainage facilities
☐ (7) Unlined rectangular cesspit NOT connected to drainage facilities
☐ (8) Lined rectangular cesspit NOT connected to drainage facilities
☐ (9) Two or three chambers septic tank connected to drainage facilities
☐ (10) Two or three chambers septic tank connected to drainage facilities
☐ (11) Others (specify)…………………………………
☐ (12) Don't know

C.2.6 Do you add any materials to it to improve the degradation?
☐ (1) Yes
☐ (2) No

C.2.7 What material do you usually use for such degradation purpose?

[insert specific name and/or take picture if possible]…………………………

C.2.8 How easily can emptying equipment access it? *(Record observation)*
☐ (1) Poor access, only accessible to hand-carried emptying equipment
☐ (2) Reasonable access for small (manual or mechanized) emptying equipment
☐ (3) Good access for medium/large size (mechanized) emptying equipment

C.2.9 Is there an access point/hatch for emptying? *(Record observation)*
☐ (1) Yes, purpose built hatch for easy access
☐ (2) Yes, but squatting plate must be removed
☐ (3) No, slab must be broken for access

Part D: Emptying practices

D.1 How do you cope when your toilet is filled?
- ☐ (1) Emptied and reused pit/tank
- ☐ (2) Abandoned and pit/tank unsealed
- ☐ (3) Abandoned with sealed cover on pit/tank
- ☐ (4) Covered and used alternative pit
- ☐ (5) Others (Specify)………………….
- ☐ (6) Don’t know

D.2 When did you empty your pit last time?

[insert years and month]…………………………

D.3 What was the reason from your last emptying?
- ☐ (1) Blocked
- ☐ (2) Overflowed
- ☐ (3) Filled
- ☐ (4) Others
- ☐ (5) Don’t know

D.4 In the last 5 years, how many times has it been emptied?
- ☐ (1) [insert number]……………………times
- ☐ (2) Don’t know

D.5 Which season (month) has it been emptied mostly?

[insert season/month]…………………………

D.6 What kind of emptying service do you usually use?
- ☐ (1) Manual
- ☐ (2) Mechanical

D.7 Do you use the same company every times you need to empty your pit?
- ☐ (1) Yes
- ☐ (2) No

D.8 How do you decide on a service provider?
- ☐ (1) Easy to contact
- ☐ (2) Quality of service provision
- ☐ (3) Best price
- ☐ (4) I have known only this company
- ☐ (5) Others (specify)………………………

D.9 How much do you pay for the service for each emptying event?

[insert number in Riels]…………………………Riels

D.10 How was the payment calculated?
- ☐ (1) Flat rate
- ☐ (2) Cost per volume removed
- ☐ (3) Other (specify)…………………

D.11 Please rate your satisfaction level for the following aspects of the emptying service? *(Tick that apply)*

Description	Very satisfied	Satisfied	Dissatisfied	Very dissatisfied
Price				
Overall service quality				
Safety				
Ease of obtaining service				

Part E: FSM improvement

E.1 Do you know where the effluents from your containment get discharged?
☐ (1) Yes (specify)……………………..
☐ (2) No

E.2 Do you care what happens to your FS?
☐ (1) Yes
☐ (2) No

E.3 Do you think FS should be treated?
☐ (1) Yes
☐ (2) No
☐ (3) Don't know (go to E.5)

E. 4. Why do you think FS should be treated/NOT treated (refer to E.3)?

[short description]……………………………………………………………………………...

……………………………………………………………………………………………………..

……………………………………………………………………………………………………..

……………………………………………………………………………………………………..

E.5 How much more are you willing to pay for emptying services that guarantee the FS is properly treated?

[insert number in Riels]………………………………………Riels

E.6 Do you have any suggestions for proper FS management in Phnom Penh?

[short description]……………………………………………………………………………...

……………………………………………………………………………………………………..

……………………………………………………………………………………………………..

……………………………………………………………………………………………………..

This is the end of the survey. Thank you!

Checklist for FS sample with emptiers

Resource Recovery for Sustainable Sanitation Management in Phnom Penh, Cambodia

Part A: Registration

Date:	
Time:	
Sample ID:	
Location (HH address such as village, commune and district name)	
Name of sample collector:	
Name of E & T service provider:	
GPS Coordination number of discharge point	X:……………………………. Y:…………………………….
Name of discharge point (record the specific name of that point if applicable, or village and commune name)	
Stage of FS collection:	☐ (1) During emptying ☐ (2) From the truck/bucket-after emptying ☐ (3) During discharge ☐ (4) Other (specify)……………………..
Household order *(Just in case the emptier has more than one clients and use the same truck, record the household order that sample was taken)*	☐ (1) First ☐ (2) Second ☐ (3) Third ☐ (4) Other (specify)………….
Amount of FS discharged from truck	☐ (1) All ☐ (2) Partial (specify below)
Describe the purpose of the keeping the remaining FS, if FS is partially discharged	

Part B: FS characteristics

B.1 Number of truck/buckets during this emptying event
- ☐ (1) One
- ☐ (2) Two
- ☐ (3) Three
- ☐ (4) Other (specify)………….

B.2 What is the volume of trucks (for motorized emptier) or the bucket (for manual emptier)?

Truck/Bucket 1:…………………………… Truck/Bucket 4: …………………………

Truck/Bucket 2:…………………………… Truck/Bucket 5: …………………………

Truck/Bucket 3:…………………………… Truck/Bucket 6: …………………………

B.3 What is the volume of FS emptied for this household?

[insert number]:……………………………m^3

B.4 How it was calculated?
[short description]:…………………………………………………………………………….

……………………………………………………………………………………………..

……………………………………………………………………………………………......

……………………………………………………………………………………………..

B.5 Is there anything added during emptying?

☐ (1) Yes (specify)……………………………………………………….
☐ (2) No

B.6 Amount added

[insert number]:……………………………m^3

B.7 Solid waste content of FS in the truck/bucket (tick that apply)

Classification	*Description*	*Tick box*
Very high solid waste content	Contains more solid wastes than faecal material	
High solid waste content	Contains significant amounts of miscellaneous solid wastes	
Medium solid waste content	Contains small amounts of miscellaneous solid wastes	
Low solid waste content	Contains some paper materials used for anal cleansing	
No solid waste content	Contains no solid wastes	

Part C: Safety practices during emptying

C.1 Did the workers wear any personal protective equipment during emptying? *(According to the observation)* (Tick all that apply)
☐ (1) Protective pant
☐ (2) Protective long sleeve jacket
☐ (3) Rubber boot
☐ (4) Gloves
☐ (5) Mask
☐ (5) No PPE at all
☐ (6) Other (specify)……………………

C.2 Was there any special clean up activity before leaving the household? (According to the observation)
☐ (1) Yes, clean with detergent/soap
☐ (2) Yes, clean only with water
☐ (3) No

C.3 Does the emptying procedure leave fecal sludge exposed in and around the household? *(According to the observation)*

☐ (1) Yes
☐ (2) No

C.4 During the transport of fecal sludge, does sludge spill into the surrounding environment? *(According to the observation during riding the along the truck to discharge site)*

☐ (1) Sludge spillage occurs along the route at various times continuously
☐ (2) Slight sludge spillage occurs at specific times (for example going down slopes or over rough ground)
☐ (3) No spillage occurs: equipment contains all of the sludge during transport
☐ (4) Other (specify)…………………..

Part D: FS disposal

D.1 How close is the disposal area to water source*? (It can be any type of water source, eg. river, steam, lake, wetlands…) (According to the observation)*

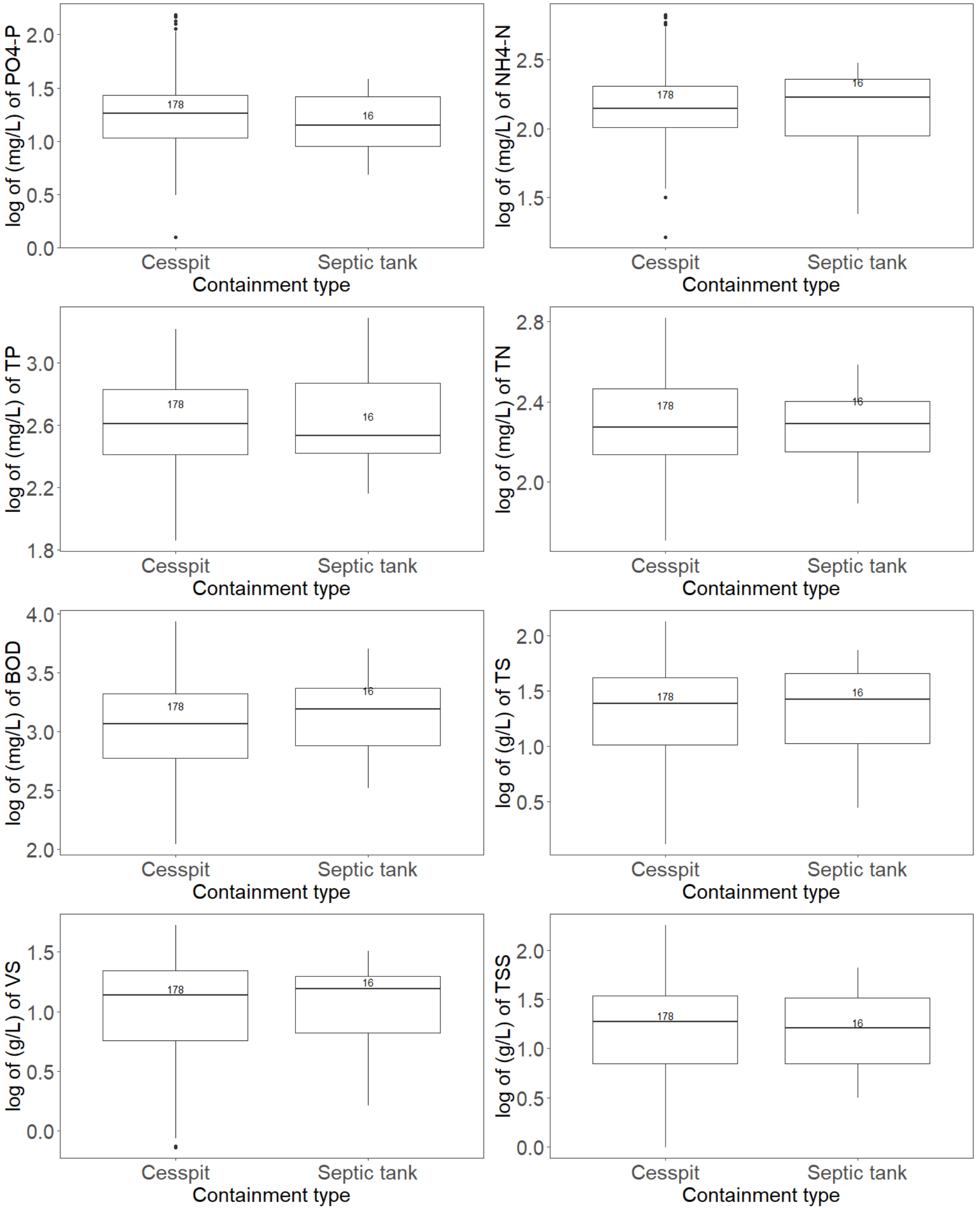
☐ (1) Less than 5 metres
☐ (2) Between 5 and 10 metres
☐ (2) More than 10 metres
☐ (4) Don't Know
☐ (5) Other (specify)………………………….

D.2 Do people come into direct contact with surface water contaminated by the disposal of FS? *(According to the observation)*

☐ (1) People come into direct contact with the contaminated surface water (for example. swimming, washing clothes, bathing)
☐ (2) People have indirect exposure to contaminated surface water (for example washing vehicles away from the water course)
☐ (3) No people are likely to come into contact with contaminated surface water
☐ (4) Don't Know
☐ (5) Other (specify)………………………….

Table S1| Summary statistics on sludge qualities from septic tanks and cesspits. For abbreviations, see text

Parameter	Minimum	Maximum	Lower quartile	Upper quartile	Median	Mean	Standard deviation
			Cesspit samples (n=178)				
pH	5.03	8.80	6.90	7.48	7.14	7.14	0.55
Conductivity (mS/cm)	0.29	4.92	0.97	1.63	1.21	1.45	0.85
Temperature (°C)	28.3	35.7	30.8	32.7	31.7	31.7	1.35
DO (mg/L)	0.29	2.90	0.37	0.52	0.44	0.52	0.34
BOD (mg/L)	111	8 600	596	2 100	1 160	1 690	1 650
TS (g/L)	1.32	134	10.3	42.1	24.5	30.9	26.9
VS (g/L)	0.73	52.8	5.73	22.1	13.7	15.5	11.9
TSS (g/L)	0.99	179	6.99	34.5	18.7	25.4	25.2
VSS (g/L)	0.29	59.1	3.87	18.3	12.0	13.1	11.3
PO_4-P (mg/L)	1.27	153	10.7	27.0	18.3	26.8	27.3
TP (mg/L)	72.9	1 640	259	673	406	498	325
NH_4-N (mg/L)	16.4	667	102	203	140	182	128
TN (mg/L)	51.2	657	137	291	187	220	113
			Septic tank sample (n=16)				
pH	5.61	7.47	6.92	7.43	7.20	7.01	0.57
Conductivity (mS/cm)	0.21	2.27	0.93	1.50	1.21	1.24	0.56
Temperature (°C)	29.7	34.9	30.8	33.0	31.5	32.0	1.50
DO (mg/L)	0.29	2.96	0.36	0.52	0.44	0.59	0.64
BOD (mg/L)	328	5 080	767	2 400	1 580	1 970	1 580
TS (g/L)	2.79	73.5	10.7	45.5	27.2	30.4	22.6
VS (g/L)	1.64	32.4	6.65	20.0	15.5	15.2	9.29
TSS (g/L)	3.14	65.9	7.09	33.1	16.3	23.8	20.5
VSS (g/L)	1.86	32.1	4.34	19.0	32.1	12.9	9.54
PO_4-P (mg/L)	4.85	38.2	9.07	26.5	14.1	18.2	11.9
TP (mg/L)	145	1 930	264	743	341	546	473
NH_4-N (mg/L)	24.0	300	90.1	230	171	160	86.0
TN (mg/L)	78.3	386	142	253	196	207	87.8


log of (mg/L) of PO4-P
2.0
1.5
1.0
0.5
0.0
178
16
Cesspit
Septic tank
Containment type
log of (mg/L) of NH4-N
2.5
2.0
1.5
178
16
Cesspit
Septic tank
Containment type
log of (mg/L) of TP
3.0
2.6
2.2
1.8
178
16
Cesspit
Septic tank
Containment type
log of (mg/L) of TN
2.8
2.4
2.0
178
16
Cesspit
Septic tank
Containment type
log of (mg/L) of BOD
4.0
3.5
3.0
2.5
2.0
178
16
Cesspit
Septic tank
Containment type
log of (g/L) of TS
2.0
1.5
1.0
0.5
178
16
Cesspit
Septic tank
Containment type
log of (g/L) of VS
1.5
1.0
0.5
0.0
178
16
Cesspit
Septic tank
Containment type
log of (g/L) of TSS
2.0
1.5
1.0
0.5
0.0
178
16
Cesspit
Septic tank
Containment type

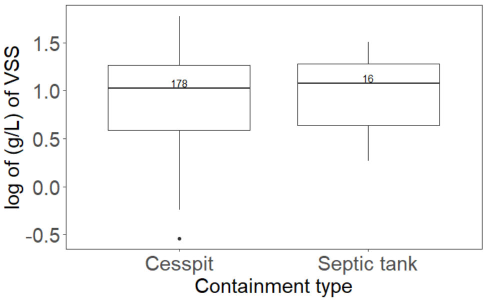


Figure S1| Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN, BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with respect to septic tank and cesspit containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

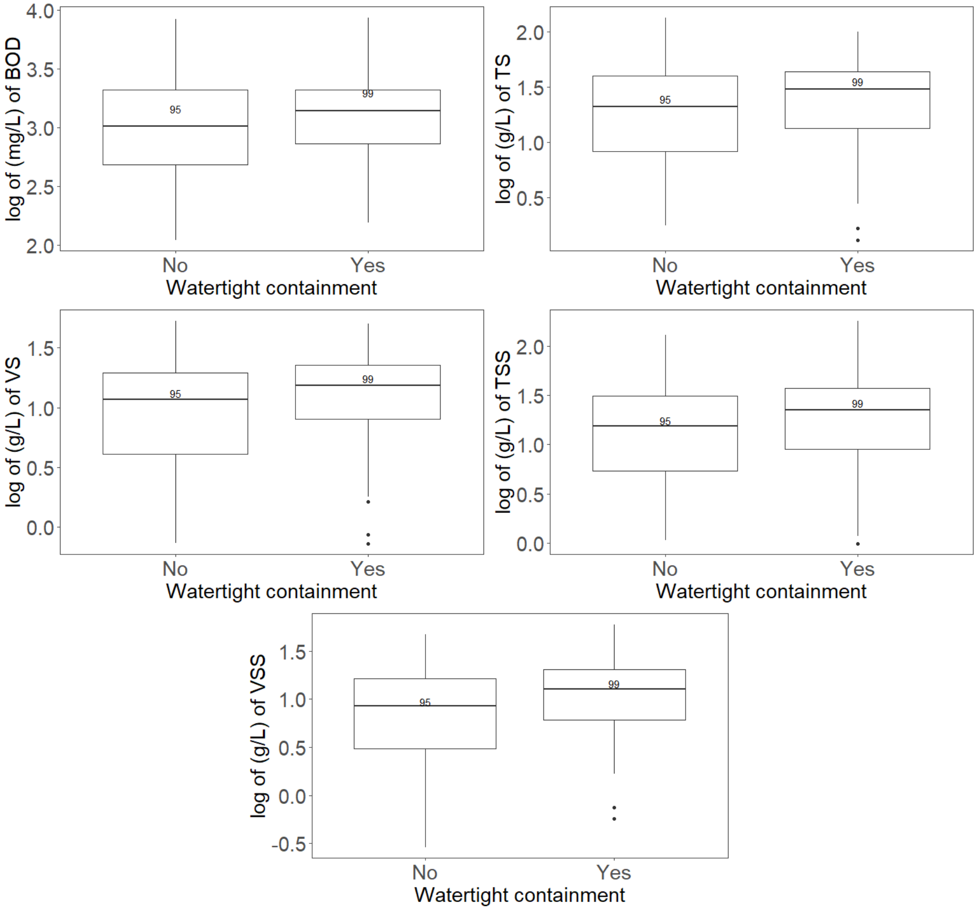


Figure S2| Boxplots of parameters studied (BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with respect to lined and unlined containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

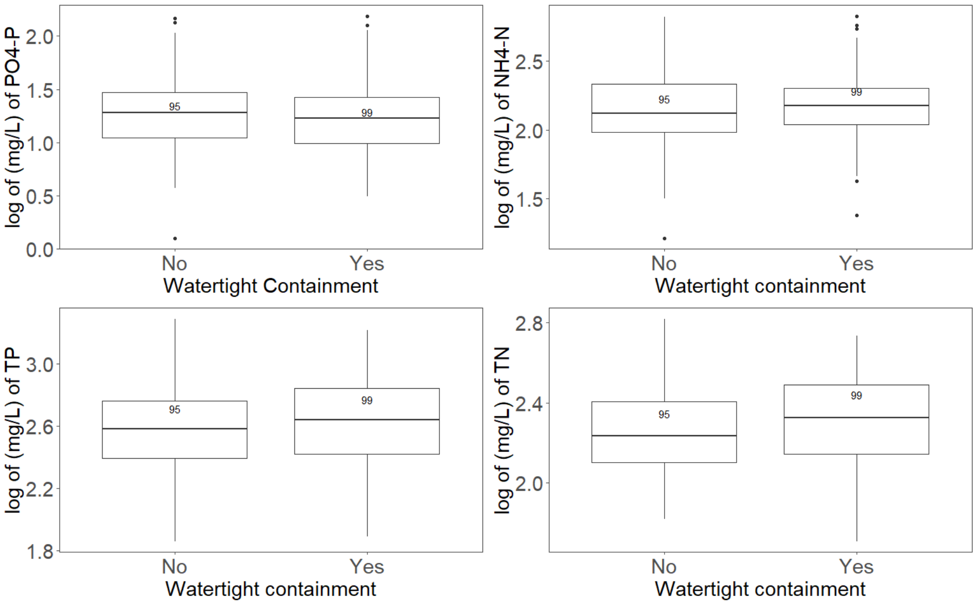


Figure S3| | Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN) in faecal sludge in Phnom Penh with respect to lined and unlined containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

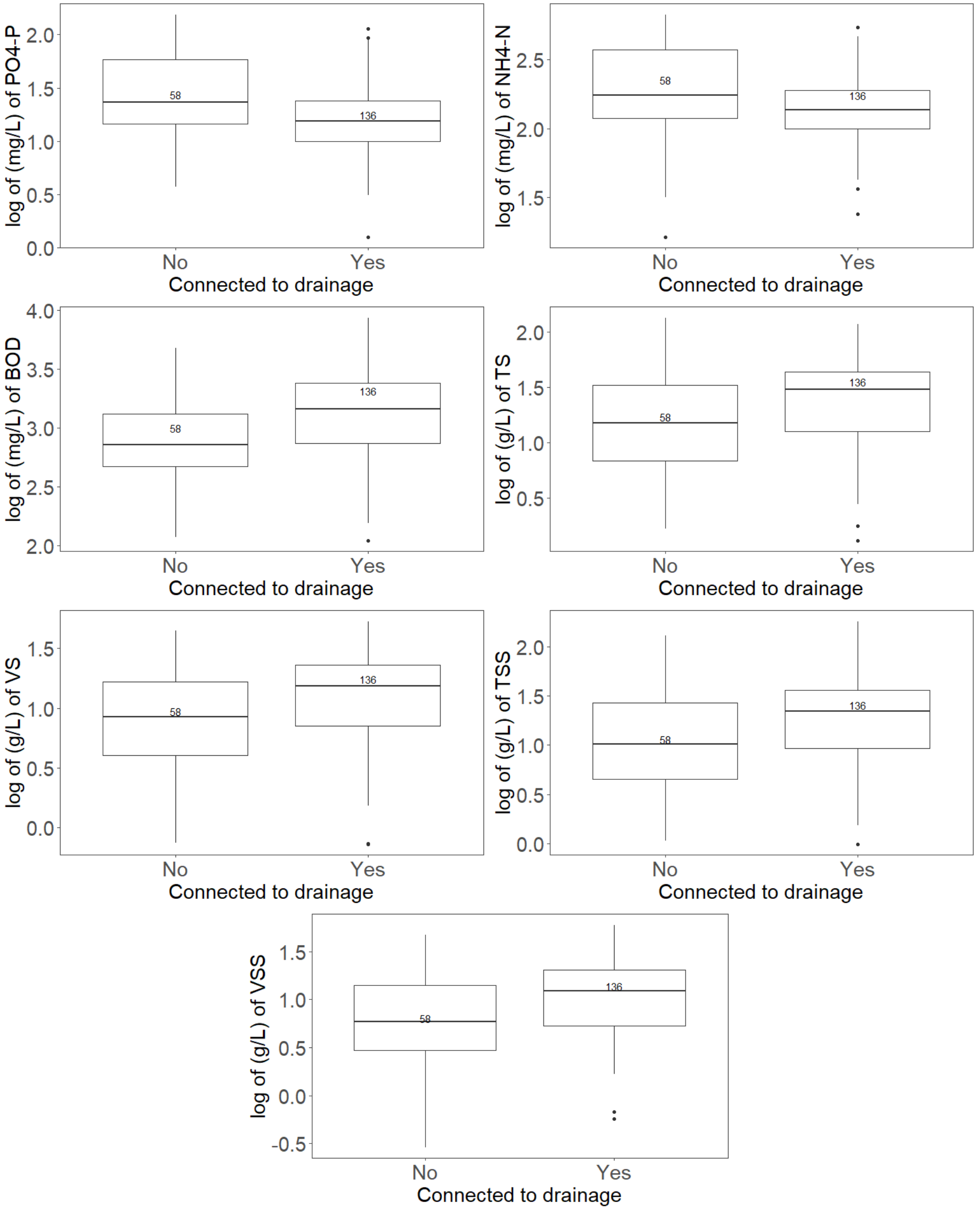


Figure S4| Boxplots of parameters studied (PO_4-P, NH_4-N, BOD, TS, VSS) in faecal sludge in Phnom Penh with regard to connection (or not) to the urban drainage network. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

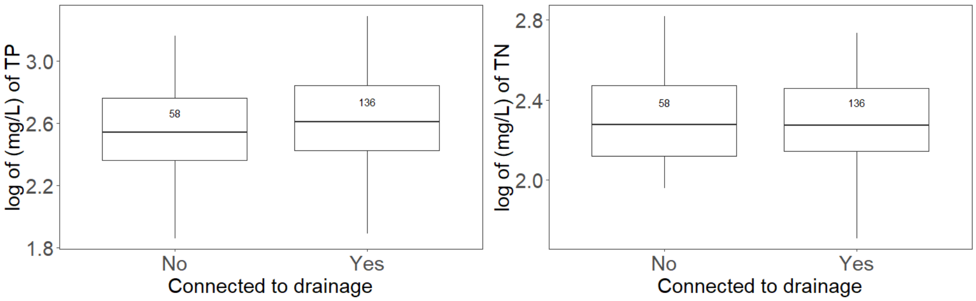


Figure S5| Boxplots of parameters studied (TP, TN) in faecal sludge in Phnom Penh with respect to connection (or not) to the urban drainage network. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

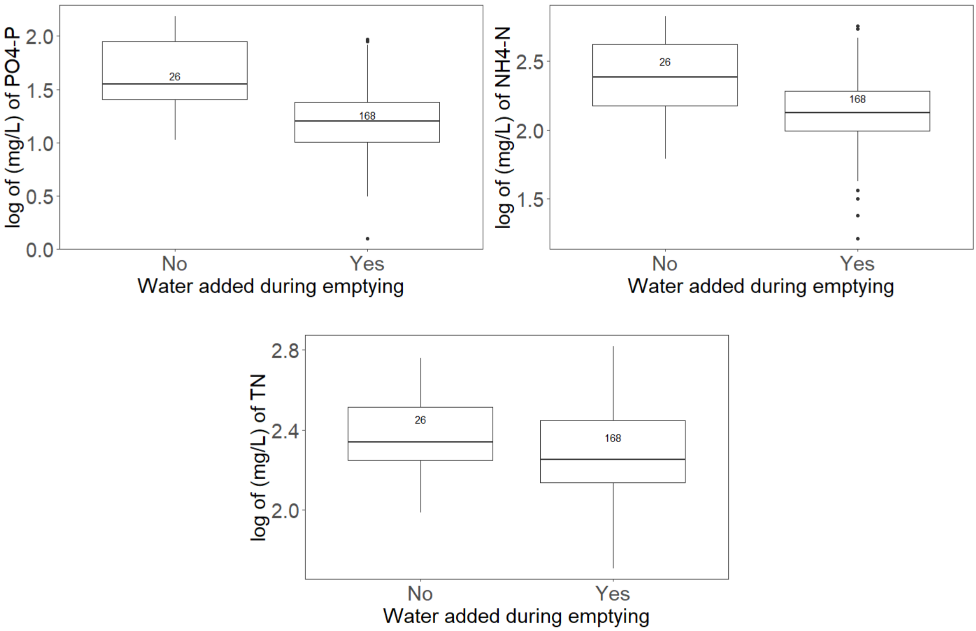


Figure S6| Boxplots of parameters studied (PO$_4$-P, NH$_4$-N, TN) in faecal sludge in Phnom Penh with regard to addition of water during septic tank/cesspit emptying. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

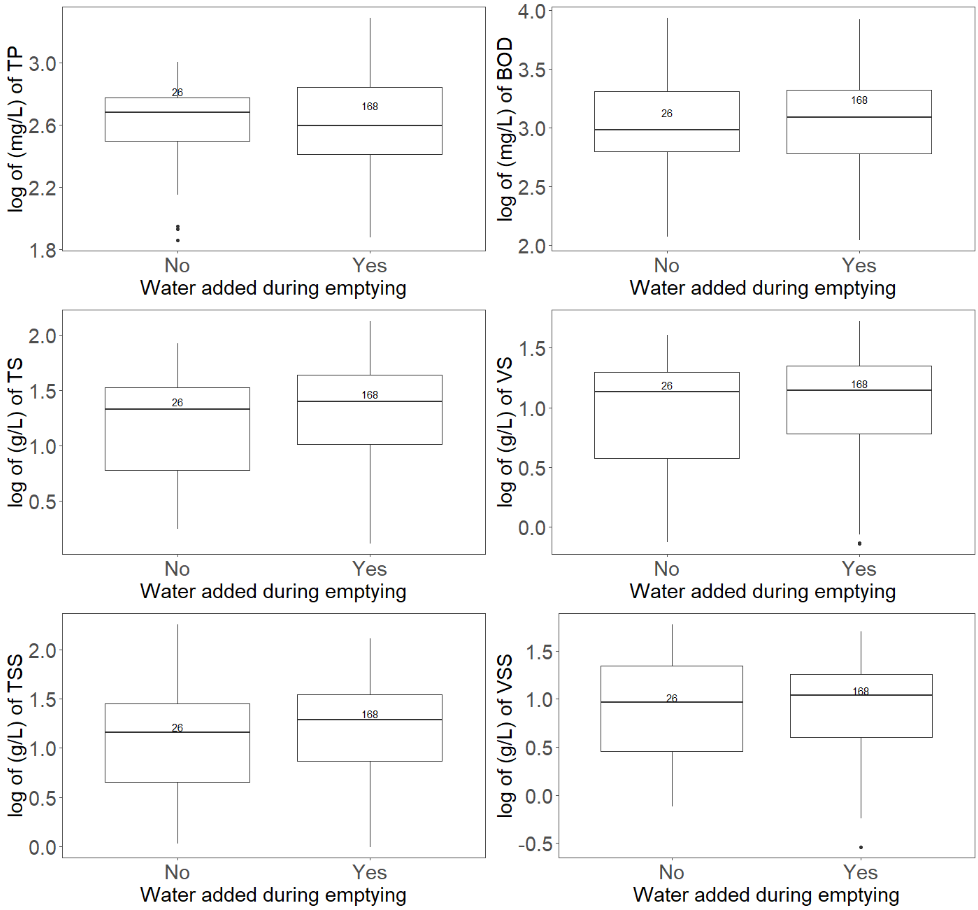


Figure S7| Boxplots of parameters studied (TP, BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with regard to addition of water during septic tank/cesspit emptying. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

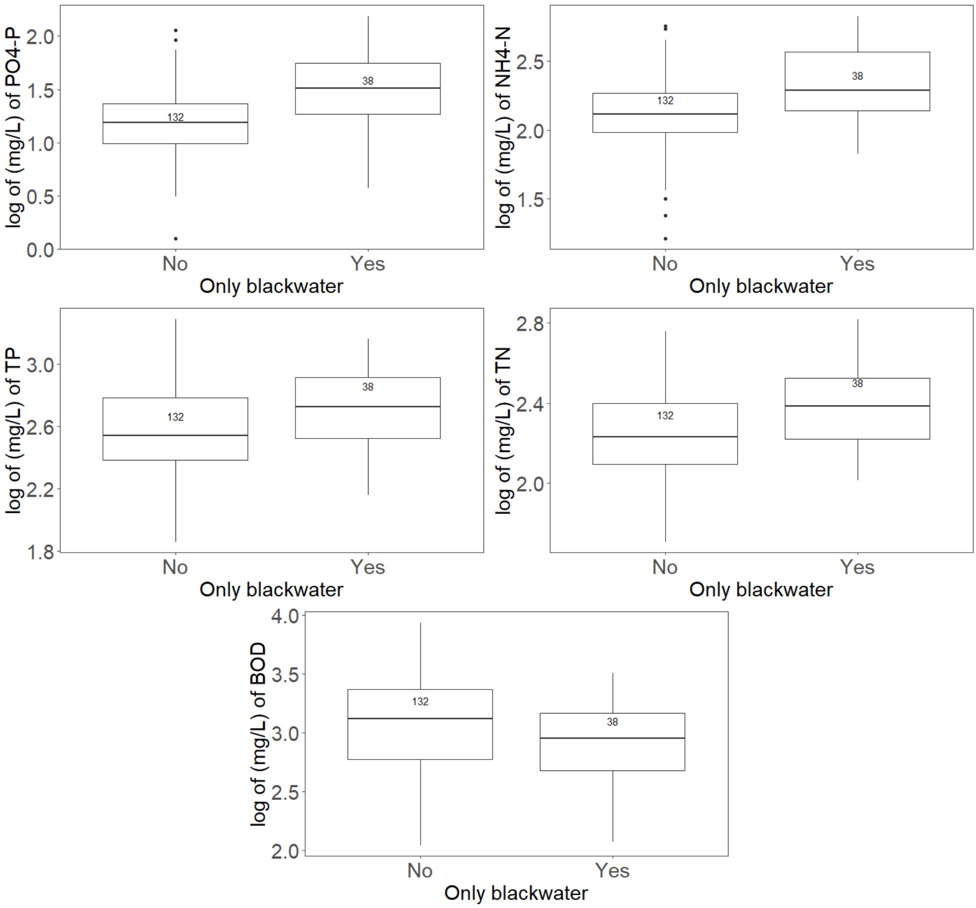


Figure S8| Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN, BOD) in faecal sludge in Phnom Penh with regard to type of wastewater collected in containment units (blackwater only or a mixture of wastewaters). Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

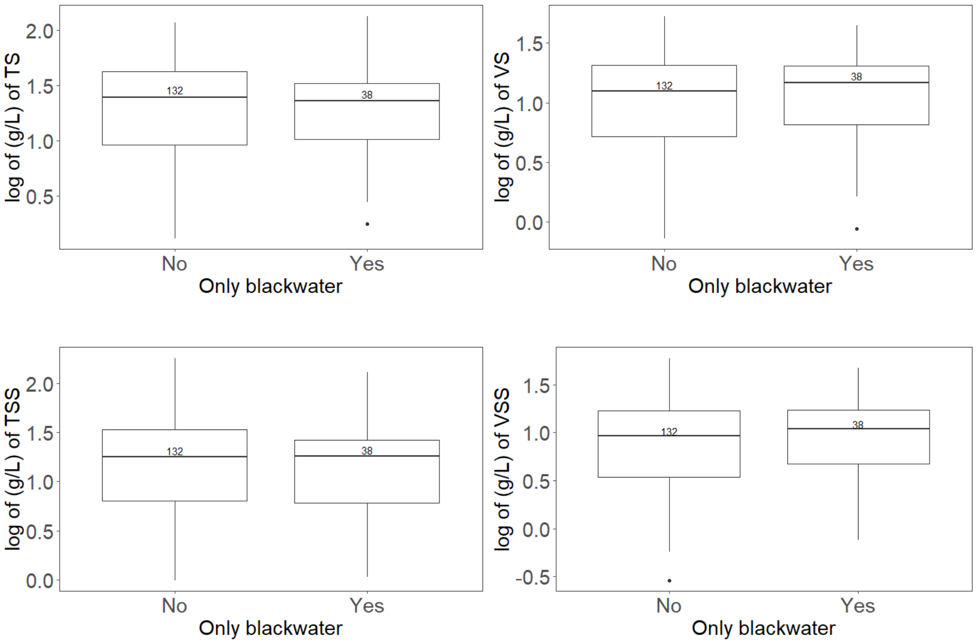
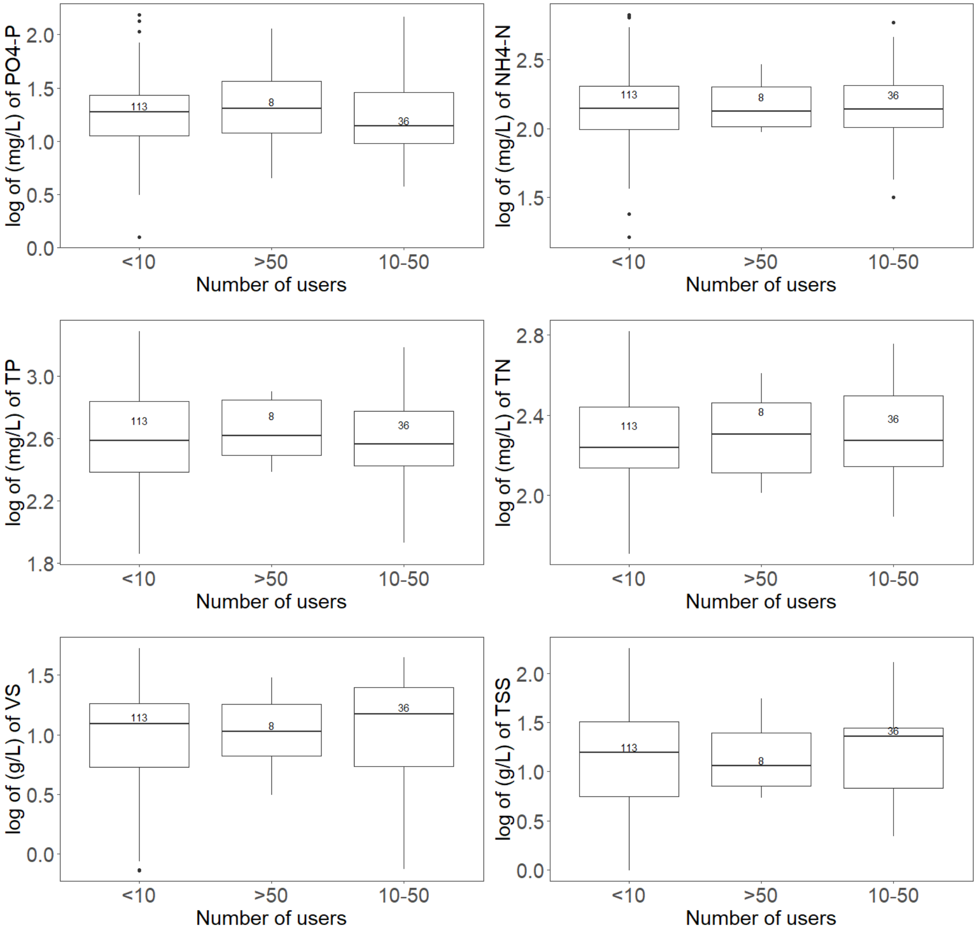


Figure S9| Boxplots of parameters studied (TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with regard to type of wastewater collected in containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.



log of (mg/L) of PO4-P
0.0
0.5
1.0
1.5
2.0
113
8
36
<10
>50
10-50
Number of users
log of (mg/L) of NH4-N
1.5
2.0
2.5
113
8
36
<10
>50
10-50
Number of users
log of (mg/L) of TP
1.8
2.2
2.6
3.0
113
8
36
<10
>50
10-50
Number of users
log of (mg/L) of TN
2.0
2.4
2.8
113
8
36
<10
>50
10-50
Number of users
log of (g/L) of VS
0.0
0.5
1.0
1.5
113
8
36
<10
>50
10-50
Number of users
log of (g/L) of TSS
0.0
0.5
1.0
1.5
2.0
113
8
36
<10
>50
10-50
Number of users

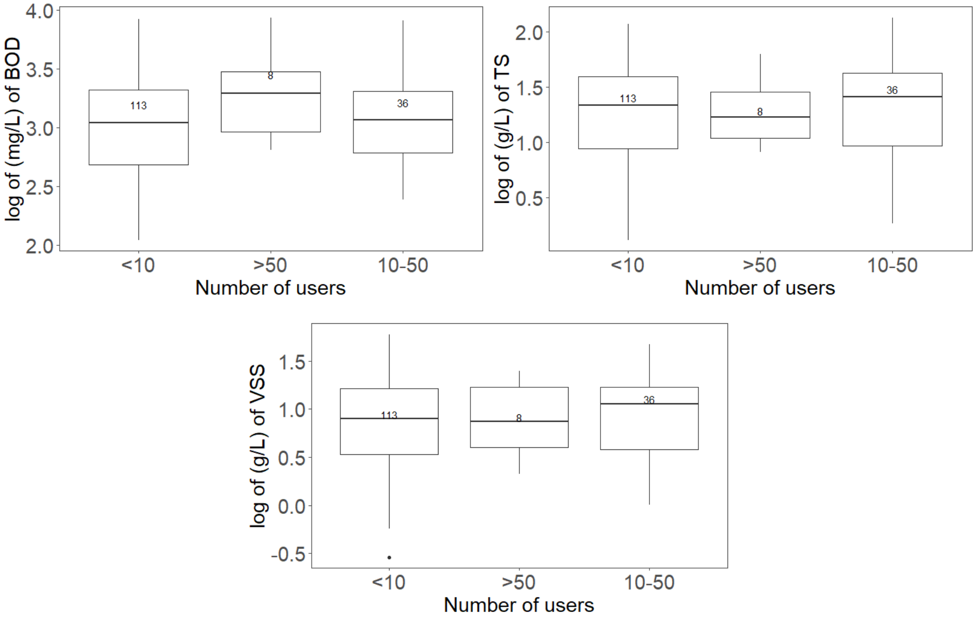
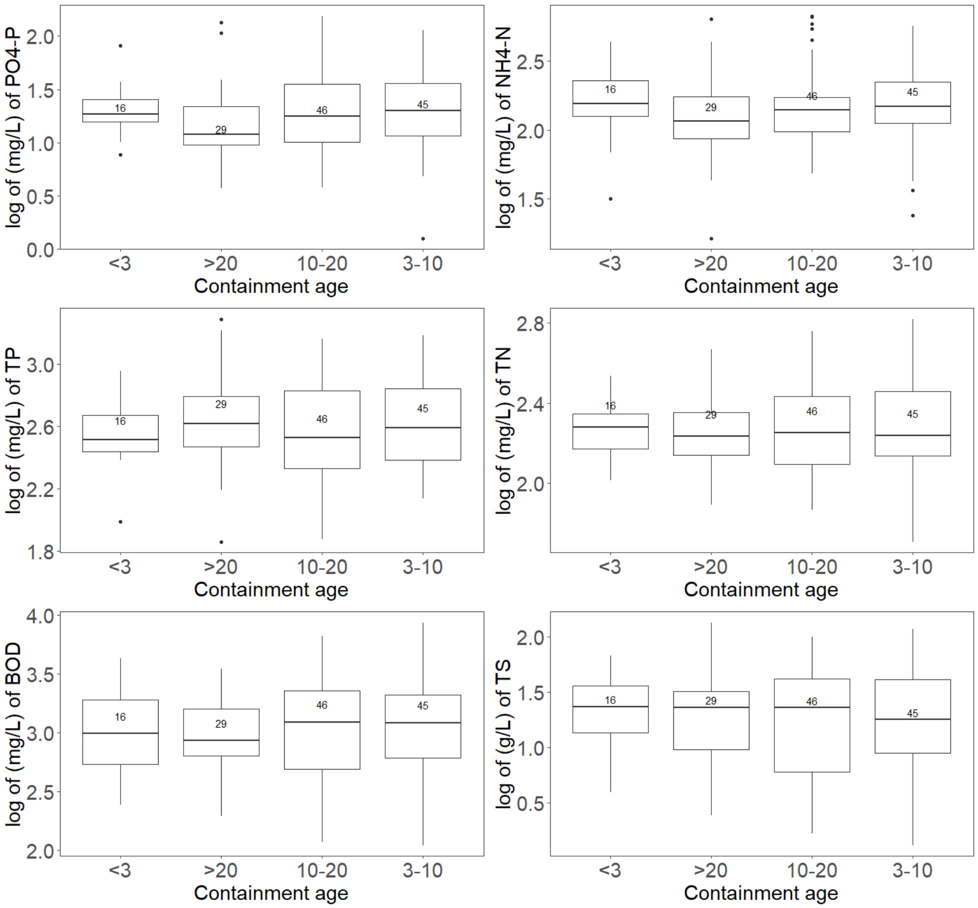


Figure S10| Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN, BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with respect to of users of the containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.


log of (mg/L) of PO4-P
0.0
0.5
1.0
1.5
2.0
16
29
46
45
<3
>20
10-20
3-10
Containment age
log of (mg/L) of NH4-N
1.5
2.0
2.5
16
29
46
45
<3
>20
10-20
3-10
Containment age
log of (mg/L) of TP
1.8
2.2
2.6
3.0
16
29
46
45
<3
>20
10-20
3-10
Containment age
log of (mg/L) of TN
2.0
2.4
2.8
16
29
46
45
<3
>20
10-20
3-10
Containment age
log of (mg/L) of BOD
2.0
2.5
3.0
3.5
4.0
16
29
46
45
<3
>20
10-20
3-10
Containment age
log of (g/L) of TS
0.5
1.0
1.5
2.0
16
29
46
45
<3
>20
10-20
3-10
Containment age

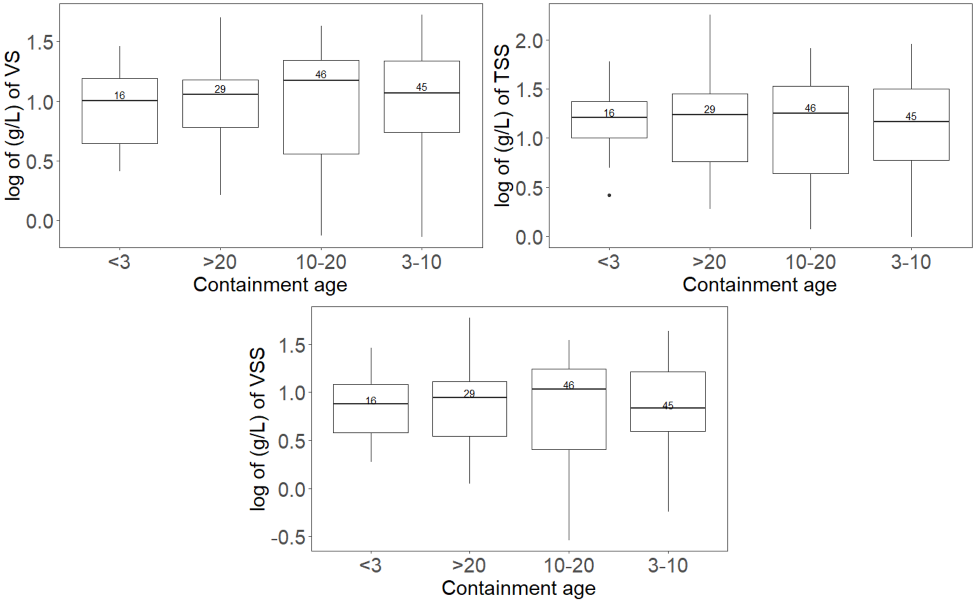


Figure S11| Boxplots of parameters studied (PO_4-P, NH_4-N, TP, TN, BOD, TS, VS, TSS, VSS) in faecal sludge in Phnom Penh with respect to the age of the containment unit. Black line in boxes and black dots outside boxes indicate median and outliers, respectively. Number on bars is number of faecal sludge samples used for calculation. For parameter abbreviations, see text.

II

frontiers | Frontiers in Environmental Science

ORIGINAL RESEARCH
published: 25 April 2022
doi: 10.3389/fenvs.2022.869009

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

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Specialty section:
This article was submitted to Water and Wastewater Management, a section of the journal Frontiers in Environmental Science

***Received:** 03 February 2022*
***Accepted:** 30 March 2022*
***Published:** 25 April 2022*

Citation:
Eliyan C, McConville JR, Zurbrügg C, Koottatep T, Sothea K and Vinnerås B (2022) Generation and Management of Faecal Sludge Quantities and Potential for Resource Recovery in Phnom Penh, Cambodia.
Front. Environ. Sci. 10:869009.
doi: 10.3389/fenvs.2022.869009

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

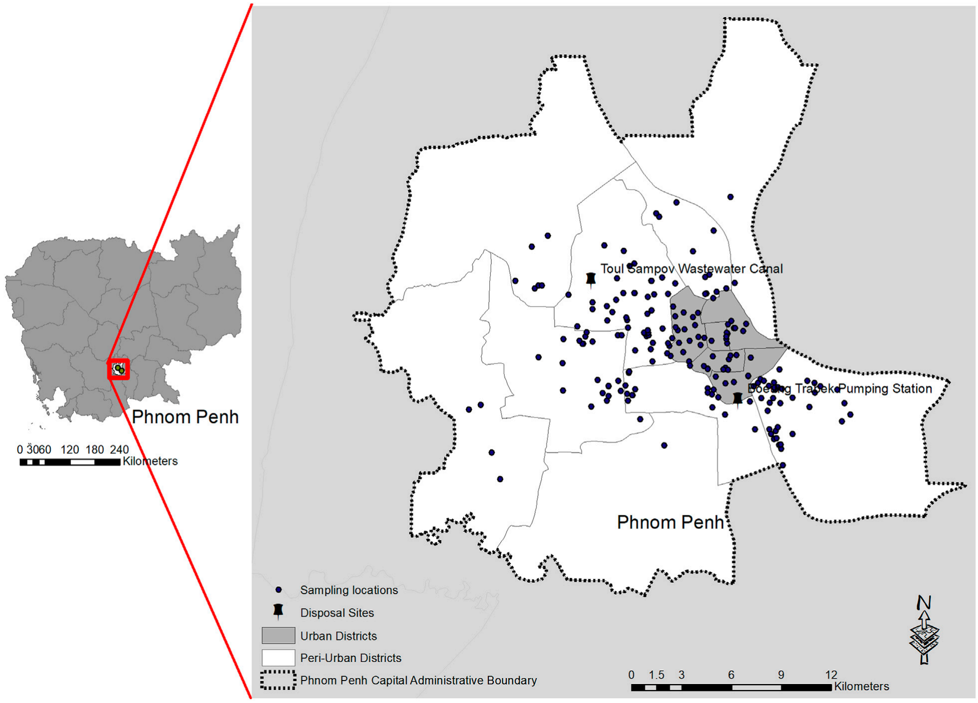

FIGURE 1 | Map showing the areas in Phnom Penh where data collection was conducted. The black dots indicate the locations of households surveyed about their sanitation management practices.

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:

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

where:

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

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:

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

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).

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

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

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

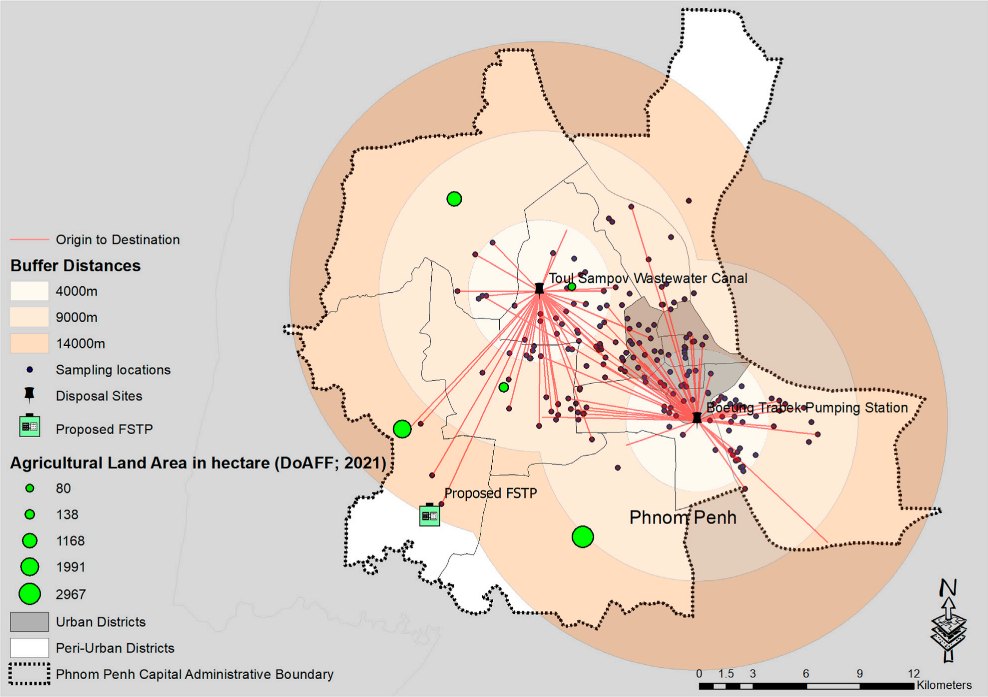

FIGURE 2 | Transport distance zones (within 4, 9 and 14 km) around Toul Sampov wastewater canal and Boeung Trabek pumping station, the two main final disposal sites of faecal sludge in Phnom Penh identified in the study.

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.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Swedish International Development Agency for fully supporting this study through the 'Sweden-Royal University of Phnom Penh Bilateral program' (Contribution No. 11599). The authors also thank Claudia von Brömssen for statistical advice and students at the Department of Environmental Science, Royal University of Phnom Penh, for their assistance during data collection in the field.

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.

frontiers | Frontiers in Environmental Science

TYPE Correction
PUBLISHED 11 August 2023
DOI 10.3389/fenvs.2023.1264993

OPEN ACCESS

EDITED AND REVIEWED BY
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RECEIVED 21 July 2023
ACCEPTED 02 August 2023
PUBLISHED 11 August 2023

CITATION
Eliyan C, McConville JR, Zurbrügg C, Koottatep T, Sothea K and Vinnerås B (2023), Corrigendum: Generation and management of faecal sludge quantities and potential for resource recovery in Phnom Penh, Cambodia.
Front. Environ. Sci. 11:1264993.
doi: 10.3389/fenvs.2023.1264993

Corrigendum: Generation and management of faecal sludge quantities and potential for resource recovery in Phnom Penh, Cambodia

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KEYWORDS

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

A Corrigendum on
Generation and management of faecal sludge quantities and potential for resource recovery in Phnom Penh, Cambodia

by Eliyan C, McConville JR, Zurbrügg C, Koottatep T, Sothea K and Vinnerås B (2022). Front. Environ. Sci. 10:869009. doi: 10.3389/fenvs.2022.869009

In the published article, there was an error in **Table 4** as published. The amount of total nitrogen (N_{total}) in faecal sludge in the original article based on the median concentration of total nitrogen was 188 mg/L (range 51.2–657 mg/L) (Eliyan et al., 2022). According to the corrigendum of Eliyan et al. (2022) the concentration of total nitrogen in Phnom Penh ranged between 1,500–3,300 mg/L and median concentration was 2,000 mg/L. The corrected **Table 4** and its caption appear below.

The authors would like to apologies for this error and state that this does not change the scientific conclusions of the article in anyway. The original article has been updated.

Publisher's note

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	—	—	64, 920
N_{tot} to Cheung Ek	—	552,000	37, 520
N_{tot} to Kob Srov	—	403,000	27, 400
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 median concentration of total nitrogen was 2000 mg/l (corrigendum of Eliyan et al., 2022) and total phosphorus was 400 mg/L (Eliyan et al., 2022). Note that it is Q_4 x concentration.

Supplementary Material

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

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Contents of this file

- Questionnaire for household survey
- Questionnaire for emptying and transportation contractor survey
- Table SI1: Socioeconomic profile of respondents stratified by household location (peri-urban and urban areas). Value in brackets are percentage of respective total. Bold indicated significant difference between peri-urban and urban settings ($p<0.05$).

Consent Form

Resource Recovery for Sustainable Sanitation Management in Phnom Penh, Cambodia

Greeting! My name is **Chea Eliyan**, a PhD student at Swedish University of Agricultural Sciences. I am conducting my PhD research on “Resource Recycling for Sustainable Sanitation Management in Phnom Penh, Cambodia”. The overall aim of the study is to identify the opportunities for safe nutrients recovery from household onsite sanitation faecal sludge, which is currently being disposed of into the environment without any treatment. This survey is part of my research to draw the baseline on households faecal sludge characteristics in Phnom Penh, to identify the environmental risk from the current faecal sludge management practices, and the potential to transfer this current system to the more circular one. Your house has been randomly selected and I would like you to participate in my study, if you decide to agree. We would ask you some questions on your households, its members and characteristics and on sanitation aspects which focus on faecal sludge, of your household. We will also take a faecal sludge sample that will be emptied by E & T service provider from your containment. The sample will be tested for physical and chemical properties at our laboratory of Department of Environmental Science, Royal University of Phnom Penh. The sample analysis will be made anonymous and the data interpretation will also be generalized as the city wide scale. Thus, the result from this study will has no any linkage back to you. The interview could approximately last for 25-30 minutes. Your participation is absolutely voluntary and you can withdraw from the survey at any time, you won’t be penalized or lose any benefits for which you otherwise qualify. You may also choose not to answer any questions. You will not have to pay to participate in this survey; nor will we pay you. The information you will be providing us will be confidential and only the researchers who are involved in this study will have access to it. Your data will also be stored without your name or any other kind of link that would enable us to identify what data is yours. Therefore, it will be available for use in future research studies forever and cannot be removed.

If you have any questions about this research study itself, please contact: Chea Eliyan, +855-17 485 675. If you feel that you have been harmed in any way by your participation in this study, please contact: Björn Vinnerås, + 46 705 521 521 or Jennifer R McConville, +46 76 783 7084.

This consent form is not a contract. It is a written explanation of what will happen during the study if you decide to participate. You are not waiving any legal rights by agreeing to participate in this study.

Could we start the interview?	☐ (1) Yes ☐ (2) No

☐ I am between 18 and 70 years old (if not, the person is not eligible to respond)

Respondent signature

Date

Questionnaire for household survey

Resource Recovery for Sustainable Sanitation Management in Phnom Penh, Cambodia

Part A: Registration

A.1 Interviewer info	Name:	Signature:
A.2 Verified by	Name:	Signature:
A.3 Interview date and start time	A.3.1 Date:	A.3.2 Time:
A.4 District		
A.5 Commune		
A.6 Village		
A.7 GPS coordinate	A.7.1 X:	A.7.2 Y:
A.8 GPS ID		
A.9 ID code		
A.10 FS ID		

Part B: General information on the household

B.1 Respondent's profile

B.1.1 Record respondent sex

☐ (1) Male
☐ (2) Female

B.1.2 Total number of family members, including respondent

[insert number]:……………………………person(s)

B.1.3 Age of respondent and family members [insert number]

☐ (1) Less than 3 years old:……………………person(s)
☐ (2) More than 3 years old:…………………… person(s)

ID	B.1.4 What is the highest education of each member in your family? (0) No formal education completed (1) Primary (grade 1-6) (2) Secondary (grade 7-9) (3) High school (grade 10-12) (4) Undergraduate (bachelor education) (6) Graduate (master education) (7) Others (specify)…………….	B.1.5 What is the primary occupation of each member? (*Record the position and institution of individual)* (1) Government (2) Private sector (3) NGOs (4) DPs (5) Others (specify)	B.1.6 What is the secondary occupation of each member? (*Record the position and institution of individual)* (1) Government (2) Private sector (3) NGOs (4) DPs (5) Others (specify)
R			

B.1.7 Are you a main income generator in your family?

☐ (1) Yes (If Yes, go to B.1.9)

☐ (2) No

B.1.8 What is the occupation of the main income generator?

☐ (1) Government

☐ (2) Private sector

☐ (3) NGOs

☐ (4) DPs

☐ (5) Others (specify)

B.1.9 Total number of family members who permanently stay at home (record the number of those who have no job outside home based on B.1.5

☐ (1) Kid (Less than 3 year old):…………………….person(s)

☐ (2) Adult (More than 3 year old:……………………person(s)

B.2 Household socio-economic

B.2.1	What kind of building does the household occupy? *(Record observation)*	☐ (1) Flat (single-storey) ☐ (2) Flat (multi-storey) ☐ (3) Simple house in a plot of land ☐ (4) Villa ☐ (6) Other (specify)……………………
B.2.2	What is the number of room occupied by your family? (Exclude kitchen, bathroom, toilet and storeroom)	[insert the number] ………………………….rooms
B.2.3	What is the size of your land? *[insert number in square meter]*	……………………….m^2
B.2.4	Is this house/residence owned or rented by a member of the household?	☐ (1) Owned and nothing to pay ☐ (2) Owned and have to pay to bank ☐ (3) Rented ☐ (4) Others (Specify) …………………

B.2.5	How long have you/ members of your household been living on this location/plot?	Enter the complete years and months …………………….......		
B.2.6	When was this house built? (Record the year that the house was completely built, or approximate the age of the building and fill NA if they don't know.	Enter the complete years or age of the building …………………….......		
B.2.7	Does your household have the following?	Item	Tick that apply	Record number
		(1) Cell phone	☐ (1) Yes ☐ (2) No	
		(2) Television	☐ (1) Yes ☐ (2) No	
		(3) efrigerator	☐ (1) Yes ☐ (2) No	
		(4) Washing machine	☐ (1) Yes ☐ (2) No	
		(5) ir conditioner	☐ (1) Yes ☐ (2) No	
		(6) ike	☐ (1) Yes ☐ (2) No	
		(7) Motorbike	☐ (1) Yes ☐ (2) No	
		(8) ar	☐ (1) Yes ☐ (2) No	
		(9) Computer (personal and desktop)	☐ (1) Yes ☐ (2) No	
		(10) an	☐ (1) Yes ☐ (2) No	
B.2.8	What is the main material of the roof? *(Record observation)*	☐ (1) Thatch/ Bamboo/Grass ☐ (2) Tile ☐ (3) Wood/plywood ☐ (4) Concrete/Brick/Stone ☐ (5) Galvanized iron/Aluminum/Other metal sheets ☐ (6) Asbestos cement sheet ☐ (7) Plastic/Synthetic material sheets ☐ (8) Others (Specify)		
B.2.9	What is the main material of the walls? *(Record observation)*	☐ (1) Thatch/Bamboo/Grass/Reeds ☐ (2) Tile ☐ (3) Wood/Plywood ☐ (4) Concrete/Brick/Stone ☐ (5) Galvanized iron/Aluminum/Other metal sheets ☐ (6) Asbestos cement sheet		

		☐ (7) Salvaged/improvised material ☐ (8) Others (Specify) ....

B.3 About water use at household

B.3.1 What is your source of water supply and drinking water source?

(Interviewer should first tick the boxes for each source that is used. Then after that, ask the respondent which one they use the most, next most, and next most…to complete the ranking)

Source of water supply	**Rank**	**Drinking water source**	**Rank**
☐ (1) Piped into dwelling	➔	☐ (1) Piped into dwelling	➔
☐ (2) Piped to yard/plot	➔	☐ (2) Piped to yard/plot	➔
☐ (3) Public tap/ standpipe	➔	☐ (3) Public tap/ standpipe	➔
☐ (4) Tube well/ borehole	➔	☐ (4) Tube well/ borehole	➔
☐ (5) Protected dug well	➔	☐ (5) Protected dug well	➔
☐ (6) Unprotected dug well	➔	☐ (6) Unprotected dug well	➔
☐ (7) Protected spring	➔	☐ (7) Protected spring	➔
☐ (8) Unprotected spring	➔	☐ (8) Unprotected spring	➔
☐ (9) Rainwater	➔	☐ (9) Rainwater	➔
☐ (10) Bottled water /gallon container and dispenser	➔	☐ (10) Bottled water /gallon container and dispenser	➔
☐ (11) Refilled bottled water	➔	☐ (11) Refilled bottled water	➔
☐ (12) Cart with small tank/ drum	➔	☐ (12) Cart with small tank/ drum	➔
☐ (13) Tanker-truck	➔	☐ (13) Tanker-truck	➔
☐ (14) Surface Water (river, dam, lake, pond, stream, canal, irrigation channels)	➔	☐ (14) Surface Water (river, dam, lake, pond, stream, canal, irrigation channels)	➔
☐ (15) Others (specify)	➔	☐ (15) Others (specify)	➔

B.3.2 How much do you pay on average for water (both drinking and general use) per month?

[insert number in Riels]…………………………………………………………………………….....

………………………………………………………………………………………………………..

………………………………………………………………………………………………………..

………………………………………………………………………………………………………..

B.3.3 How would you rate the cost of the water for your household? *(It is based on the reaction of the respondent during the interview and tick the box where appropriate)*

☐ (1) Very cheap

☐ (2) Inexpensive (at the affordable rate)

☐ (3) Expensive

☐ (4) Very expensive

☐ (5) Don’t know/ No comment

B.3.4 What is the average quantity of water do you use per month? *[ask for water invoice from previous months if piped water source, otherwise some calculation may be needed]*

[insert number in cubic meter]…………………………………………………………………....

……………………………………………………………………………………………………..

……………………………………………………………………………………………………..

……………………………………………………………………………………………………..

Part C: Sanitation technology

C.1 About toilet (user interface)

C.1.1 How many toilet does your household own?

☐ (1) One

☐ (2) Two

☐ (3) Three

☐ (4) Four

☐ (5) Five

☐ (6) More than 5 (specify)………………………

C.1.2 What kind of toilet facility do members of your household usually use? (Multiple answers are possible) *[Record observation or ask question where applicable] (Enumerator use the printed pictures about the type of toilet to show householder to add visualization and get more accurate answers)*

Number of toilets	*Types of toilet*
………………………	☐ (1) Automatic cistern Flush
………………………	☐ (2) Pour/manual flush
………………………	☐ (3) Ventilated improved pit latrine
………………………	☐ (4) Pit latrine with slab
………………………	☐ (5) Pit latrine without slab/open pit
………………………	☐ (6) Composting toilet
………………………	☐ (7) Bucket
………………………	☐ (8) Hanging toilet
………………………	☐ (9) Others (specify)……………………..

C.1.3 Do you share any of these toilets with other households?

☐ 1. Yes

☐ 2. No (If NO go to C.1.6)

C.1.4 How many other **households** share this toilet?

☐ [insert number of households]………………….household(s)

☐ Don't Know

C.1.5 How many other **persons** (in that households) share this toilet?

☐ [insert number of persons]…………………………person(s)

☐ Don't Know

C.1.6 When these toilets were built? *Multiple answers are possible according to the number of toilet they might have (refer to C.1.1 and C.1.2)*

[insert number of years and months]…………………………………………………………

………………………………………………………………………………………………

………………………………………………………………………………………………

………………………………………………………………………………………………

C.1.7 Do you have access to toilet inside the house?

☐ (1) Yes

☐ (2) No

C.1.8 Do you use water for cleaning after using the toilet?

☐ (1) Yes

☐ (2) No

C.1.9 Do you use tissue paper for cleaning after using the toilet?

☐ (3) Yes

☐ (4) No

C.1.9 Are there any other materials (excluding water and tissue paper) do you use for cleaning after using the toilet?

☐ (3) Yes (specify)………………………………

☐ (4) No

C.2 About the containment (This section is designed to seek for detailed information about the containment that is being emptied during that emptying event. No matter how many containments the household has, please refer to the one that is being emptied)

C.2.1 Where are the contents of the toilet discharged?

(Enumerator use the printed pictures about the type of containments to show householder to add visualization and get more accurate answers)

☐ (1) One or more unlined circular cesspit connected to drainage facilities

☐ (2) One or more lined circular cesspit connected to drainage facilities

☐ (3) One or more unlined circular cesspit NOT connected to drainage facilities

☐ (4) One or more lined circular cesspit NOT connected to drainage facilities

☐ (5) Unlined rectangular cesspit connected to drainage facilities

☐ (6) Lined rectangular cesspit connected to drainage facilities

☐ (7) Unlined rectangular cesspit NOT connected to drainage facilities

☐ (8) Lined rectangular cesspit NOT connected to drainage facilities

☐ (9) Two or three chambers septic tank connected to drainage facilities

☐ (10) Two or three chambers septic tank connected to drainage facilities

☐ (11) Others (specify)…………………………………

☐ (12) Don’t know

C.2.2 When was this containment built? *(This is referred to the containment that was connected to toilet and being emptied)*

[insert number of years and months]…………………………

C.2.3 Do you dispose of wastewater from kitchen, bathing and/or laundry to the same containment as toilet? *(This is to clarify if the wastewater goes to same containment as the above-mentioned toilet. Do not explain the purpose but simply ask and tick the respondent’s answer).*

☐ (1) Yes, they all go to the same containment (Go to C.2.6)

☐ (2) Yes, wastewater from kitchen goes to the same containment as toilet (Go to C.2.5)

☐ (3) Yes, Wastewater from bathing and laundry go to the same containment as toilet (Go to C.2.4)

☐ (4) No, they all have separated containment (Go to C.2.4)

C.2.4 Where do you dispose of wastewater from kitchen?

☐ (1) One or more unlined circular cesspit connected to drainage facilities

☐ (2) One or more lined circular cesspit connected to drainage facilities

☐ (3) One or more unlined circular cesspit NOT connected to drainage facilities

☐ (4) One or more lined circular cesspit NOT connected to drainage facilities

☐ (5) Unlined rectangular cesspit connected to drainage facilities

☐ (6) Lined rectangular cesspit connected to drainage facilities

☐ (7) Unlined rectangular cesspit NOT connected to drainage facilities

☐ (8) Lined rectangular cesspit NOT connected to drainage facilities

☐ (9) Two or three chambers septic tank connected to drainage facilities

☐ (10) Two or three chambers septic tank connected to drainage facilities

☐ (11) Others (specify)…………………………………

☐ (12) Don't know

C.2.5 Where do you dispose of wastewater from bathing and laundry?

☐ (1) One or more unlined circular cesspit connected to drainage facilities

☐ (2) One or more lined circular cesspit connected to drainage facilities

☐ (3) One or more unlined circular cesspit NOT connected to drainage facilities

☐ (4) One or more lined circular cesspit NOT connected to drainage facilities

☐ (5) Unlined rectangular cesspit connected to drainage facilities

☐ (6) Lined rectangular cesspit connected to drainage facilities

☐ (7) Unlined rectangular cesspit NOT connected to drainage facilities

☐ (8) Lined rectangular cesspit NOT connected to drainage facilities

☐ (9) Two or three chambers septic tank connected to drainage facilities

☐ (10) Two or three chambers septic tank connected to drainage facilities

☐ (11) Others (specify)…………………………………

☐ (12) Don't know

C.2.6 Do you add any materials to it to improve the degradation?

☐ (1) Yes

☐ (2) No

C.2.7 What material do you usually use for such degradation purpose?

[insert specific name and/or take picture if possible]…………………………

C.2.8 How easily can emptying equipment access it? *(Record observation)*

☐ (1) Poor access, only accessible to hand-carried emptying equipment

☐ (2) Reasonable access for small (manual or mechanized) emptying equipment

☐ (3) Good access for medium/large size (mechanized) emptying equipment

C.2.9 Is there an access point/hatch for emptying? *(Record observation)*

☐ (1) Yes, purpose built hatch for easy access
☐ (2) Yes, but squatting plate must be removed
☐ (3) No, slab must be broken for access

Part D: Emptying practices

D.1 How do you cope when your toilet is filled?

☐ (1) Emptied and reused pit/tank
☐ (2) Abandoned and pit/tank unsealed
☐ (3) Abandoned with sealed cover on pit/tank
☐ (4) Covered and used alternative pit
☐ (5) Others (Specify)………………….
☐ (6) Don’t know

D.2 When did you empty your pit last time?

[insert years and month]…………………………

D.3 What was the reason from your last emptying?

☐ (1) Blocked
☐ (2) Overflowed
☐ (3) Filled
☐ (4) Others
☐ (5) Don’t know

D.4 In the last 5 years, how many times has it been emptied?

☐ (1) [insert number]……………………times
☐ (2) Don’t know

D.5 Which season (month) has it been emptied mostly?

[insert season/month]…………………………

D.6 What kind of emptying service do you usually use?

☐ (1) Manual
☐ (2) Mechanical

D.7 Do you use the same company every times you need to empty your pit?

☐ (1) Yes

☐ (2) No

D.8 How do you decide on a service provider?

☐ (1) Easy to contact

☐ (2) Quality of service provision

☐ (3) Best price

☐ (4) I have known only this company

☐ (5) Others (specify)………………………

D.9 How much do you pay for the service for each emptying event?

[insert number in Riels]…………………………Riels

D.10 How was the payment calculated?

☐ (1) Flat rate

☐ (2) Cost per volume removed

☐ (3) Other (specify)………………….

D.11 Please rate your satisfaction level for the following aspects of the emptying service? *(Tick that apply)*

Description	**Very satisfied**	**Satisfied**	**Dissatisfied**	**Very dissatisfied**
Price				
Overall service quality				
Safety				
Ease of obtaining service				

Part E: FSM improvement

E.1 Do you know where the effluents from your containment get discharged?

☐ (1) Yes (specify)……………………..

☐ (2) No

E.2 Do you care what happens to your FS?

☐ (1) Yes

☐ (2) No

E.3 Do you think FS should be treated?

☐ (1) Yes

☐ (2) No

☐ (3) Don’t know (go to E.5)

E. 4. Why do you think FS should be treated/NOT treated (refer to E.3)?

[short description]……………………………………………………………………………...

…………………………………………………………………………………………………….

…………………………………………………………………………………………………….

…………………………………………………………………………………………………….

E.5 How much more are you willing to pay for emptying services that guarantee the FS is properly treated?

[insert number in Riels]…………………………………………Riels

E.6 Do you have any suggestions for proper FS management in Phnom Penh?

[short description]……………………………………………………………………………...

…………………………………………………………………………………………………….

…………………………………………………………………………………………………….

…………………………………………………………………………………………………….

.

This is the end of the survey. Thank you!

Questionnaire for emptying and transportation contractor

Resource Recovery for Sustainable Sanitation Management in Phnom Penh, Cambodia

Part A: Registration

Date:	
Time:	
Sample ID:	
Location (HH address such as village, commune and district name)	
Name of sample collector:	
Name of E & T service provider:	
GPS Coordination number of discharge point	X:…………………………….. Y:……………………………..
Name of discharge point (record the specific name of that point if applicable, or village and commune name)	
Stage of FS collection:	☐ (1) During emptying ☐ (2) From the truck/bucket-after emptying ☐ (3) During discharge ☐ (4) Other (specify)……………………..
Household order *(Just in case the emptier has more than one clients and use the same truck, record the household order that sample was taken)*	☐ (1) First ☐ (2) Second ☐ (3) Third ☐ (4) Other (specify)…………
Amount of FS discharged from truck	☐ (1) All ☐ (2) Partial (specify below)
Describe the purpose of the keeping the remaining FS, if FS is partially discharged	

Part B: FS characteristics

B.1 Number of truck/buckets during this emptying event

☐ (1) One

☐ (2) Two

☐ (3) Three

☐ (4) Other (specify)…………

B.2 What is the volume of trucks (for motorized emptier) or the bucket (for manual emptier)?

Truck/Bucket 1:…………………………… Truck/Bucket 4: …………………………

Truck/Bucket 2:…………………………… Truck/Bucket 5: …………………………

Truck/Bucket 3:…………………………… Truck/Bucket 6: …………………………

B.3 What is the volume of FS emptied for this household?

[insert number]:……………………………m^3

B.4 How it was calculated?

[short description]:……………………………………………………………………………….

……………………………………………………………………………………………….

…………………………………………………………………………………………….....

……………………………………………………………………………………………….

B.5 Is there anything added during emptying?

☐ (1) Yes (specify)…………………………………………………….

☐ (2) No

B.6 Amount added

[insert number]:……………………………m^3

B.7 Solid waste content of FS in the truck/bucket (tick that apply)

Classification	*Description*	*Tick box*
Very high solid waste content	Contains more solid wastes than faecal material	
High solid waste content	Contains significant amounts of miscellaneous solid wastes	
Medium solid waste content	Contains small amounts of miscellaneous solid wastes	
Low solid waste content	Contains some paper materials used for anal cleansing	
No solid waste content	Contains no solid wastes	

Part C: Safety practices during emptying

C.1 Did the workers wear any personal protective equipment during emptying? *(According to the observation)* (Tick all that apply)

☐ (1) Protective pant

☐ (2) Protective long sleeve jacket

☐ (3) Rubber boot

☐ (4) Gloves

☐ (5) Mask

☐ (5) No PPE at all

☐ (6) Other (specify)……………………

C.2 Was there any special clean up activity before leaving the household? (According to the observation)

☐ (1) Yes, clean with detergent/soap

☐ (2) Yes, clean only with water

☐ (3) No

C.3 Does the emptying procedure leave fecal sludge exposed in and around the household? *(According to the observation)*

☐ (1) Yes

☐ (2) No

C.4 During the transport of fecal sludge, does sludge spill into the surrounding environment? *(According to the observation during riding the along the truck to discharge site)*

☐ (1) Sludge spillage occurs along the route at various times continuously

☐ (2) Slight sludge spillage occurs at specific times (for example going down slopes or over rough ground)

☐ (3) No spillage occurs: equipment contains all of the sludge during transport

☐ (4) Other (specify)…………………..

Part D: FS disposal

D.1 How close is the disposal area to water source*? (It can be any type of water source, eg. river, steam, lake, wetlands…) (According to the observation)*

☐ (1) Less than 5 metres

☐ (2) Between 5 and 10 metres

☐ (2) More than 10 metres

☐ (4) Don’t Know

☐ (5) Other (specify)………………………….

D.2 Do people come into direct contact with surface water contaminated by the disposal of FS? *(According to the observation)*

☐ (1) People come into direct contact with the contaminated surface water (for example. swimming, washing clothes, bathing)

☐ (2) People have indirect exposure to contaminated surface water (for example washing vehicles away from the water course)

☐ (3) No people are likely to come into contact with contaminated surface water

☐ (4) Don’t Know

☐ (5) Other (specify)………………………….

Demography of respondents

Respondents to the survey were stratified by geographic location. It reveals that gender, educational level employment status, household size, and access to water for general use were not impacted by geographical location of the households (Table SI1). Interestingly, type and age of the building are impacted by geographical location of the respondents. More respondents in peri-urban setting occupy multiple-storey buildings compared to the urban dwellers (p=0.012), while number of ageing houses (>20years) appear significantly higher in urban area (p<0.001).

Table SI1| Socioeconomic profile of respondents stratified by household location (peri-urban and urban areas). Value in brackets are percentage of respective total. Bold indicated significant difference between peri-urban and urban settings (p<0.05)

Variables	Total 195 (%)	Peri-urban 144 (%)	Urban 51 (%)	p-value
Gender				
Female	93 (47.7)	68 (47.2)	25 (49.0)	0.954
Male	102 (52.3)	76 (52.8)	26 (51.0)	0.954
Educational level				
No formal education completed	11 (5.6)	6 (4.9)	5 (11.1)	0.166
Primary (grade 1-6)	26 (13.3)	22 (17.9)	4 (8.9)	0.235
Secondary (grade 7-9)	38 (19.5)	30 (24.4)	8 (17.8)	0.484
High school (grade 10-12)	45 (23.1)	31 (25.2)	14 (31.1)	0.569
Undergraduate (Bachelor education)	47 (24.1)	33 (26.8)	14 (31.1)	0.723
Graduate (master education)	1 (0.5)	1 (0.8)	0 (0.0)	
Primary employment status				
Business	75 (39.5)	54 (38.3)	21 (42.9)	0.694
Government	24 (12.6)	19 (13.5)	5 (10.2)	0.730
Private sector	36 (19.0)	26 (18.4%	10 (20.4)	0.927
Other	55 (28.9)	42 (29.8%)	13 (26.5)	0.802
Secondary employment status				
Yes	13 (6.9)	8 (5.7)	5 (10.2)	0.325
No	176 (93.1)	132 (94.3)	44 (89.8)	0.358
Household size (number of persons)				
1-3	46 (25.0)	30 (22.2)	16 (32.7)	0.210
4-6	89 (48.4)	67 (49.7)	22 (44.9)	0.688
7-9	22 (11.9)	16 (11.8)	6 (12.2)	1.000
>9	27 (14.7)	22 (16.3)	5 (10.2)	0.425
Type of building				
Flat (single- storey)	18 (9.2)	14 (9.7)	4 (7.8)	0.786
Flat (multi-storey)	73 (37.4)	46 (31.9)	27 (52.9)	**0.012**
Simple house in a plot of land	60 (30.8)	49 (34.0)	11 (21.6)	0.138
Villa	15 (7.7)	10 (7.0)	5 (9.8)	0.544
Other	29 (14.9)	25 (17.4)	4 (7.8)	0.157

Variables	Total 195 (%)	Peri-urban 144 (%)	Urban 51 (%)	p-value
Age of the building (number of years)				
<3	23 (13.0)	20 (14.9)	3 (7.0)	0.276
3-10	70 (39.5)	61 (45.6)	9 (20.9)	**0.007**
11-20	60 (33.9)	44 (32.8)	16 (37.2)	0.732
>20	24 (13.6)	9 (6.7)	15 (34.9)	**<0.001**
Access to water for general use				
Piped water into dwelling	194 (99.5)	143 (99.3)	51 (100)	
Surface water	1 (0.5)	1 (0.7)	0 (0.0)	

Journal of Environmental Management 349 (2024) 119436

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Heavy metal contamination of faecal sludge for agricultural production in Phnom Penh, Cambodia

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ARTICLE INFO

Handling Editor: Raf Dewil

Keywords:
Faecal sludge management
Heavy metals
Low and middle-income country
Nutrient recovery
Onsite sanitation
Sustainable agriculture

ABSTRACT

To achieve the universal target of 'safely managed sanitation' set out in UN Sustainable Development Goal 6, the world needs to increase its rate of progress, since e.g. Phnom Penh, the capital of Cambodia, currently has zero percent safely managed sanitation. One way to promote safer faecal sludge management is to shift to a more circular system with nutrient recycling, but this carries the risk of heavy metal accumulation in the environment. This study analysed the concentrations of heavy metals in raw faecal sludge from various sources and assessed the appropriateness of resource recovery and reuse in relation to the heavy metal and nutrient loads in faecal sludge. A total of 42 samples collected from sludge disposal sites in Phnom Penh during the dry and rainy seasons were analysed for heavy metals and physicochemical parameters. Mean measured concentrations of heavy metals in faecal sludge samples decreased in the order Zn > Cu > Pb > Cr > Ni > Hg > As > Cd in both seasons but were higher in the rainy season, probably due partly to inflow from stormwater drains and run-off from roads during storm events. All elements analysed were within the permissible limits for application to land according to EU standards and USEPA. However, Hg and Zn concentrations exceeded the tolerance limits for local organic fertiliser and Swedish limits for compost. Faecal sludge is thus not an appropriate fertiliser considering the risk of heavy metal accumulation in relation to phosphorus recovered. Options to avoid recirculating pollutants to the environment include upstream prevention of pollution, source separation of household wastewater fractions and use of biosolids as a soil conditioner together with other fertilisers or for soil production. Additional studies are needed on these options if sanitation stakeholders are to close the nutrient loop.

1. Introduction

The world will likely fail to achieve universal access to safely managed sanitation coverage in 2030, as set out in UN Sustainable Development Goal 6, target 6.2, if it continues with its current rate of progress, with 2.8 billion people still without a safe sanitation service (WHO & UNICEF, 2021). Onsite sanitation currently plays a key role in meeting the sanitation needs of around 2.7 billion of the world's population and this number is expected to reach 5 billion by 2030 (Strande, 2014). Approximately 1 billion onsite facilities worldwide are in urban areas (Strande, 2014). Indiscriminate disposal of the large quantities of faecal sludge generated by these facilities could lead to outbreaks of disease, as well as causing environmental pollution, eutrophication of waters and loss of the aesthetic beauty of nature (Kuffour et al., 2013). Therefore, safe management of faecal sludge is needed to avoid negative impacts on public health and the environment (Zewde et al., 2021). However, safe management of faecal sludge involves addressing the whole sanitation service chain, including collection, emptying and transportation, processing and safe disposal (Strande et al., 2014; Boot and Scott, 2008).

Many cities in low- and middle-income countries have poor faecal sludge management, with no legal framework and almost no services. For example, Phnom Penh, the capital of Cambodia, has 0% safely managed faecal sludge generated from onsite sanitation facilities and

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https://doi.org/10.1016/j.jenvman.2023.119436
Received 6 July 2023; Received in revised form 2 October 2023; Accepted 20 October 2023

the sludge often ends up in the immediate urban environment, posing risks to public health and the environment (PPCA, 2021). For instance, diarrhoea is one of the primary contributors to global disease burden and faecal contamination attributed 88% of the cases (Otoo et al., 2015). A recent study in Phnom Penh revealed that households only empty their sludge container when it is overfilled or clogged (Eliyan et al., 2022a). This indicates a lack of regular emptying, which is a requirement to ensure proper performance of septic tanks, leading to poor performance of the system. Only 22% of Phnom Penh city dwellers report having their container emptied, while only 12% of the sludge collected reaches the authorised disposal site (Peal et al., 2015). The indiscriminate dumping of untreated faecal sludge contributes significantly to surface water and ground water pollution (Krithika et al., 2017), e. g eutrophication from excess nutrients can negatively impact the functions of natural ecosystem (Andersson et al., 2016).

Viewing human waste as a potential resource could enable a paradigm shift towards sustainable sanitation and faecal sludge management, thus avoiding associated environmental and health risks. Instead of indiscriminate disposal in the open environment and in local neighbourhoods, safe faecal sludge management through recovery of nutrients could improve sanitation and benefit the agriculture sector (Chandana and Rao, 2022). Sludge treatment is urgently needed to prevent pollution and to handle the large quantities of faecal sludge generated (Michael Steiner et al., 2002). In addition, different forms of treatment end-products could be recovered from faecal sludge, e.g. its high organic matter content makes it suitable for biogas production through anaerobic digestion (Ahmed et al., 2019) or as a soil amendment in crop production (Zewde et al., 2021). Its high calorific value is adequate for bioenergy generation or use as biofuel (Hafford et al., 2018). Other forms of resource that can be recovered from faecal sludge include building materials, protein, animal feedstuffs and water for irrigation (Andriessen et al., 2019; Diener et al., 2014).

Protecting public health is a precondition for reuse of faecal sludge in agriculture (Tayler, 2018). The WHO and United States Environmental Protection Agency (USEPA) have established guidelines for using treated waste (biosolids) that require components defined as Class A and Class B biosolids to meet limits for pathogen removal and pollutant concentrations (WHO, 2006; USEPA, 1994). Pathogen removal can be achieved by use of appropriate treatment technologies, e.g. some studies report almost 100% pathogen inactivation and low helminth egg viability through thermophilic composting of faecal sludge (Strande et al., 2014; WHO, 2006). In contrast, heavy metals are very challenging to remove during treatment of faecal sludge and pose threats to human health and the environment if they accumulate in soil (Shamuyarira and Gumbo, 2014). Even in middle and high income countries where pathogenic hazards from wastewater are likely controlled, there is growing concerns about heavy metals and other chemicals contaminants in reuse systems (Manzoor Qadir et al., 2015). Therefore, information on the concentrations of heavy metals in faecal sludge in relation to the concentrations of available nutrients is necessary when planning resource recovery.

Previous studies have found that concentrations of heavy metals in faecal sludge vary based on season and source. For example, a study in Dar es Salaam, Tanzania, found a significant difference between the dry and rainy seasons in conductivity value and total solids concentration in pit latrine sludge (Doglas et al., 2021). Yet, it may be difficult to extrapolate data from African studies to the Asian context. The majority (58%) of onsite containment systems in African cities are pit latrines whereas Asian cities commonly have waterborne containment systems that discharge to open drain (Peal et al., 2020). For instance, water based toilet connected to onsite containment units is predominantly used by residents in Phnom Penh (Eliyan et al., 2022a). Therefore, local data are needed for proper planning and to ensure there are no potential risks associated with changing from current practices to a circular

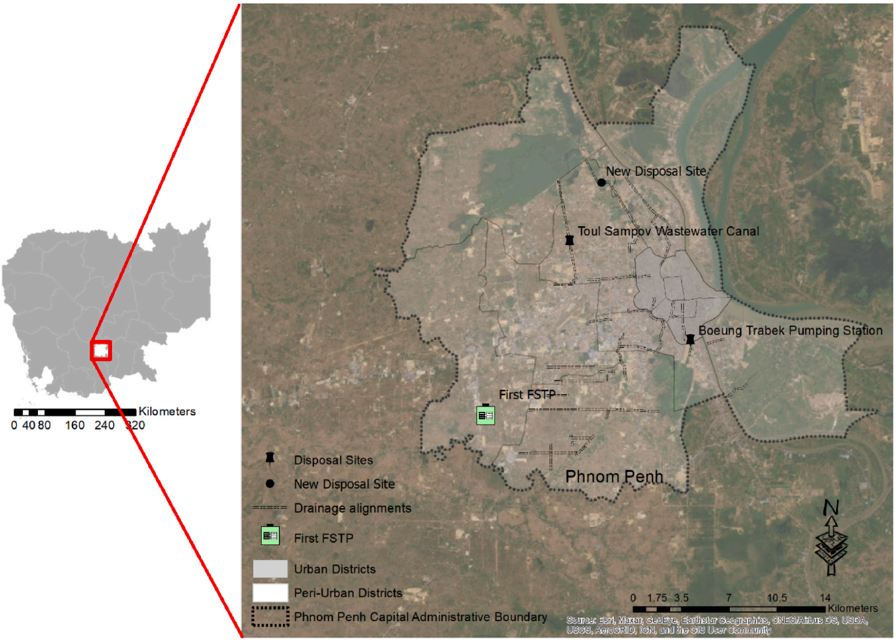

Fig. 1. (Left) Map of Cambodia showing the location of the study area and (right) satellite image of Phnom Penh showing where faecal sludge samples were collected during the rainy season (Toul Sampov wastewater canal and Boeung Trabek pumping station) and dry season (new disposal site and Boeung Trabek pumping station).

system (Chandana and Rao, 2022).

The aims of the present study were to determine the concentrations of heavy metals in raw faecal sludge from various sources and to assess the appropriateness of resource recovery and reuse in relation to heavy metal and nutrient concentrations in faecal sludge. Specific objectives were to: 1) identify whether there are seasonal variations in heavy metal concentrations in faecal sludge from different sources in Phnom Penh; 2) assess whether faecal sludge can be classified as biosolids based on national and international standards for heavy metal concentrations; and 3) provide baseline data on heavy metal concentrations in faecal sludge in relation to the plant nutrient content, to support sanitation stakeholders in selecting appropriate faecal sludge management technologies for resource recovery in Phnom Penh.

2. Methods

Faecal sludge samples for the study were collected from disposal sites identified in a previous study as the main locations receiving sludge collected from household containment units in Phnom Penh (Eliyan et al., 2022a). The characteristics of the samples obtained were analysed both onsite and at the laboratory.

2.1. Study area

The study area was the city of Phnom Penh, located at 11°34″N, 104°55″E on the Mekong floodplain, above the confluence of the Mekong, Tonle Sap and Bassac rivers (JICA, 2016). The city is undergoing rapid development and is now divided into 14 districts classified as urban areas (5 districts) and peri-urban areas (9 districts). The total population of Phnom Penh is around 2 million, with approximately 500, 000 households (NIS, 2020). There are typically two seasons in Cambodia, a rainy season (June to October) and a dry season (November to May). According to mean monthly rainfall data for the period 2004–2013, February had the lowest precipitation level (8.1 mm) and September had the highest (272.4 mm), followed by October (244 mm) (JICA, 2016). The wettest month shifted to October in 2020, while February remained the driest month, according to reports from the Cambodian Ministry of Water Resources and Meteorology.

Onsite sanitation is the predominant sanitation system used in Phnom Penh (Peal et al., 2015; Frenoux et al., 2011). There are two types of onsite containment system, cesspits and septic tanks. Cesspits are by far the most common system, serving over 90% of households in both urban and peri-urban districts of Phnom Penh. Regardless of the type of containment system they use, 95% of households in urban districts have the overflow from their containment system connected to a sewer network, while only 63% of peri-urban households have such a connection (Eliyan et al., 2022a). There is no legal requirement on regular emptying of containment systems and most Phnom Penh households have their containment unit emptied only when it is clogged (57%) or full (35%).

There is only one faecal sludge treatment plant in Phnom Penh at present, and it was opened only recently (19 May 2023). Previously, Boeung Trabek pumping station (Cheung Ek wetland) was the only authorised faecal sludge disposal site (JICA, 2016). However, a recent study by Eliyan et al. (2022a) identified further disposal sites (possibly unauthorised) in addition to Boeung Trabek pumping station, such as public manholes near households, fields around the Kob Srov area, Toul Sampov wastewater canal and a smaller canal (approximately 1 km length) connected to Toul Sampov wastewater canal. That study concluded that wherever faecal sludge is disposed of within the drainage network, it ends up in the two main receiving reservoirs (Cheung Ek and Kob Srov wetlands). Such indiscriminate disposal of faecal sludge in Phnom Penh has also been reported in other studies (PPCA, 2021).

The faecal sludge samples analysed in the present study were mainly collected at the two main disposal spots, i.e. Boeung Trabek pumping station and Toul Sampov wastewater canal (Fig. 1). However, during dry season sampling of faecal sludge it was found that there were no incoming trucks discharging sludge into Toul Sampov wastewater canal, due to recent enforcement by the local authority of a ban on indiscriminate disposal of faecal sludge around the canal area, with a fine of 500 USD applied to operators contravening the ban. To overcome this challenge, local operators have begun to use a new disposal site located in northern Phnom Penh that is also connected to Kob Srov wetland, i.e. the wetland is still the recipient of all faecal sludge collected in the area. Dry season sampling of faecal sludge (28 January-12 February 2023; n = 7 samples) for the present study was conducted at the new disposal site, instead of the Toul Sampov wastewater canal site. Wet season sampling was conducted earlier (2–15 October 2022), when Toul Sampov was still an active disposal site.

2.2. Screening step before collecting faecal sludge samples

An initial screening was performed to determine whether samples needed be taken from all incoming trucks at each sampling site. Screening criteria were source of faecal sludge and consent from emptying and transportation operator. A decision was made to exclude industrial sources and a temporary containment system in the study area, since sludge from industrial sources was expected to differ significantly from that from other sources and since the temporary containment system served a construction site for a new shopping mall and would disappear once construction ended. If extracted faecal sludge arriving at the sampling sites was from non-industrial sources and from permanent containment systems and if consent was granted, a sample was taken.

2.3. Faecal sludge sampling procedure

The sampling design took into account variations between the seasons in Phnom Penh. A total of 42 faecal sludge samples were collected, with 21 samples each in the rainy and dry seasons. Before actual sampling began, site observations were conducted to confirm whether the preliminary sampling plan and sites were applicable. Before rainy season sampling, a week of observations revealed that Boeung Trabek pumping station received more frequent discharges than Toul Sampov wastewater canal. This agreed with previous findings that Boeung Trabek pumping station receives around 60% of total faecal sludge discharge in Phnom Penh (Eliyan et al., 2022a). Therefore, in the rainy and dry seasons, the initial plan was to collect 28 samples from Boeung Trabek pumping station and 14 samples from Toul Sampov wastewater canal. Since the discharged ratio between Boeung Trabek pumping station and Toul Sampov wastewater canal is approximately 2:1, the sampling strategy is representative. When the new site for dry season sampling was identified, it replaced the seven dry-season samples that were planned to be collected from Toul Sampov wastewater canal. The faecal sludge dumped at the disposal sites comes from various sources, but this study focused only on sludge extracted from containment systems serving households, rented houses, apartments and restaurants.

Faecal sludge sampling was designed based on findings in a previous study in Phnom Penh that three factors significantly influence faecal sludge characteristics in the city: i) addition of water during emptying, ii) connection to urban drainage network and iii) type of wastewater captured by household containment systems (Eliyan et al., 2022b). Specific location (urban vs peri-urban) and type of containment unit (septic tank vs cesspit) were thus not critical factors contributing to the variation in faecal sludge characteristics in that study. Sampling was conducted at sludge disposal sites, since they are the key targets for construction of treatment plants (Koottatep et al., 2021). The first sampling round (rainy season) was performed during 2–15 October 2022 (since October was the wettest month in 2020) and the second sampling round (dry season) during 28 January-2 February 2023 (since February was the driest month in 2004–2013 and in 2020). Each sampling round consisted of seven alternate sampling days within the

Table 1
Physicochemical properties of faecal sludge samples collected in Phnom Penh in the dry and rainy seasons. SD = standard deviation, P-values <0.05 indicate statistically significant difference between dry and rainy seasons, (–) indicates data not available.

Parameter	Both seasons (n = 42)			Dry season (n = 21)					Rainy season (n = 21)					P-value
	Median	Mean	SD	Min	Max	Median	Mean	SD	Min	Max	Median	Mean	SD	
Conductivity (mS/cm)	1.5	1.8	0.99	0.62	4.9	1.5	1.8	1.0	0.64	4.5	1.5	1.7	0.98	0.586
DO (mg/L)	0.56	0.56	0.090	0.42	0.82	0.57	0.58	0.08	0.43	0.83	0.53	0.54	0.092	0.157
pH	7.1	6.9	0.60	5.4	8.3	7.1	7.0	0.62	5.5	7.6	7.0	6.9	0.59	0.484
Temp (°C)	29	29	1.4	27	33	30	30	1.7	28	32	29	29	1.1	0.266
TS (%)	1.9	2.9	2.9	0.52	10	2.1	2.9	2.4	0.30	13	1.4	2.9	3.5	0.261
VS (%)	69	62	18	33	84	72	64	17	13	90	63	61	19	0.517
NH_4–N (g/L)	–	–	–	0.04	0.68	0.11	0.16	0.14	–	–	–	–	–	–
TN (g/L)	–	–	–	1.5	3.3	2.0	2.2	0.65	–	–	–	–	–	–
PO_4–P (g/L)	–	–	–	0.01	0.68	0.61	0.10	0.14	–	–	–	–	–	–
TP (g/L)	–	–	–	0.22	2.5	0.23	0.47	0.65	–	–	–	–	–	–

selected two-week period. On each sampling day, the study team waited for incoming trucks at each disposal site and collected faecal sludge samples from any incoming trucks that met the screening criteria. During sampling, the study team asked the contractor to begin discharging the sludge as usual and, after 1 min of discharge, a sample was collected in a 1-L polypropylene bottle and subjected to recommended sample handling and preservation techniques (APHA, AWWA and WEF, 2017).

2.4. Faecal sludge analysis and quality control

The collected samples were immediately analysed onsite for the following parameters: Conductivity, dissolved oxygen (DO), pH and temperature (Temp), using a HORIBA-U-52G multi-parameter water meter. Regular calibration of the instrument was performed before each sampling day to ensure accurate measurement. The samples were then placed in an ice box and transported to the Department of Environmental Science Laboratory, Royal University of Phnom Penh, for further analysis. At the laboratory, gravimetric analysis method 2540G (drying, cooling, desiccating and weighing) was used for determination of total solids (TS) and volatile solids (VS) content. Sub-samples were then pretreated by drying at 103–105 °C and sent to Bureau Veritas (Cambodia) Limited Laboratory, where the concentrations of arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) were determined by microwave digestion (methods MARS 6 and ICPMS-7700), where the detection limit for As, Cd, Cr, Cu, Hg, Ni, Pb and Zn was 0.1, 1, 1, 2, 0.02, 1, 1 and 2 μg/L, respectively. The blank spiked recovery rate of all elements in rainy season samples was: As 9.5%, Cd 90.1%, Cr 104% Cu 107%, Hg 120%, Ni 98%, Pb 114% and Zn 90%. In dry season samples it was: As 93.2%, Cd 97.7%, Cr 101% Cu 104% Hg 90.1%, Ni 93.7%, Pb 98.9% and Zn 98%.

The dry-season samples were preserved by adding H_2SO_4 to obtain $pH < 2$ (APHA, AWWA and WEF, 2017) and frozen for transport to the laboratory at the Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), for nutrient analysis (ammonia nitrogen (NH_4–N), total nitrogen (TN), phosphate-phosphorus (PO_4–P) and total phosphorus (TP)). Merck test kits were used for all nutrient analyses, following the manufacturer's instructions. A two-step approach was employed for determination of TN. The first step was digestion (Spectroquant Crack set Cat. No. 1.14963) to transform organic and inorganic nitrogen compounds into nitrate according to Koroleff's method by using oxidising agents in a thermo-reactor at 120 °C for 1 h. According to the manufacturer's instructions, chemical oxygen demand (COD) acts as interference if it exceeds 0.35 g/L. Other studies have found that COD in faecal sludge can range from 8 to 122 g/L (Ward et al., 2021; Junglen et al., 2020; Ahmed et al., 2019; Afolabi and Sohail, 2017; Bassan et al., 2013). Thus the COD concentration in faecal sludge samples is generally high and a high dilution factor is needed to reduce it to a level that will not consume the oxidising agent, leaving organic and inorganic nitrogen compounds in the digested solution. Here, the amount of oxidising reagent needed to be doubled to ensure complete transformation of nitrogenous compounds in the faecal sludge samples. The digestion solution was then analysed using the Spectroquant Nitrate test (Cat. No. 1.09713) and Spectroquant Ammonium cell test (Cat. No. 1.14559). Similarly, a two-step process was employed to analyse TP (Spectroquant Crack set Cat. No. 1.14687), where the digestion solution was analysed following PO_4–P analysis by colorimetric methods, using a Thermo Scientific Gallery™ discrete analyser.

2.5. Statistical analysis

The analytical data obtained were computed in Microsoft Excel (2010), and R software version 4.0.4 (R Core Team, 2021) was used for data analysis. Descriptive statistic tools were used to assess faecal sludge characteristics across all samples and by season. According to the central limit theorem, the mean of observations could be assumed normally distributed when sample size is large enough (>20). The non-parametric method (Wilcoxon's rank sum test) was used to check for statistically significant differences between seasons for parameters that were not normally distributed, such as TS, VS, As, Cd, Cr, Cu, Hg, Ni, Pb and Zn, while the two sample *t*-test was applied for data with a normal distribution, such as Conductivity, DO, pH and Temp. Half the limit of quantification value was applied for calculation of heavy metal content in relation to P recovered.

3. Results

Households (including apartment and rented houses) were the dominant source of faecal sludge collected, representing 93% of total samples, while other source (apartments) made up 7%. Approximately 67% of faecal sludge samples collected were from peri-urban districts, while other locations including urban districts of Phnom Penh and two nearby cities (Oudong and Ta Khmau) contributed the remainder. Oudong, in Kampong Speu province, lies approximately 35 km northwest of Phnom Penh and Ta Khmau, the largest city in Kandal province, lies about 11 km south of Phnom Penh. The majority of sludge samples collected were black (62%), with other colours such as dark brown, brown, light brown and yellow together representing 38%.

3.1. Nutrient content in faecal sludge

The parameters measured in the field (Conductivity, DO, pH, Temp) did not show statistically significant differences between seasons (Table 1). However, the mean value of all parameters was generally lower in rainy-season than in dry-season samples. The range of values obtained for dry-season samples was: Conductivity 0.62–4.9 mS/cm, DO 0.42–0.82 mg/L, pH 5.4–8.3 and Temp 29–33 °C. Similar ranges were found for all parameters in rainy-season samples.

The concentrations of TS, VS, NH_4–N, TN, PO_4–P and TP showed high variation, uneven distribution and high standard deviation

Table 2
Summary statistics on heavy metal concentrations (mg/kg) in faecal sludge samples collected in Phnom Penh in the dry and rainy seasons. All values expressed on a dry mass basis (mg/kg total solids, TS). Values in bold indicate significant difference between the seasons ($P < 0.05$).

Parameter	Dry season (n = 21)					Rainy season (n = 21)					P-value
	Min	Max	Median	Mean	SD	Min	Max	Median	Mean	SD	
Non-essential heavy metals											
As	0.28	5.7	1.1	1.7	1.6	2.8	15	4.4	5.4	3.0	**<0.001**
Cd	<1[a]	2.3	<1[a]	–	–	<1[a]	2.2	1.1	–	–	**0.011**
Hg	1.1	16	3.7	4.9	3.6	<0.02[a]	16	3.1	5.3	5.1	0.654
Pb	1.4	17	10	9.2	3.9	9.1	112	46	49	27	**<0.001**
Essential heavy metals											
Cr	<1[a]	13	3.8	4.1	2.7	22	72	40	43	13	**<0.001**
Cu	15	670	79	120	130	67	280	160	150	61	**0.0062**
Ni	2.5	57	14	21	17	12	30	18	19	5.3	0.102
Zn	810	1900	1300	1200	330	320	4300	1600	1600	900	0.184

[a] Below limit of quantification.

(Table 1). The standard deviation was almost as high as the mean value of the respective parameter in all cases. The TS and VS content in faecal sludge samples did not differ significantly between the rainy-season and dry-season samples. In dry-season samples, the TS content as 0.52–0% and the VS content 33–84%TS, while in rainy-season samples the range was 0.30–13% for TS and 13–90%TS for VS. The mean values of both TS and VS were generally lower in rainy-season samples. Only dry season data were available for NH$_4$–N, TN, PO$_4$–P and TP concentrations, so comparison between the seasons was not applicable. The mean concentration (±standard deviation) of NH$_4$–N and TN was 0.16 ± 0.14 g/L and 2.2 ± 0.65 g/L, respectively (range 0.04–0.68 g/L and 1.5–3.3 g/L, respectively). The mean concentration (±standard deviation) of PO$_4$–P and TP was 0.10 ± 0.14 g/L and 0.47 ± 0.65 g/L, respectively.

3.2. Seasonal variation in heavy metal loads in faecal sludge

Summary statistics on measured heavy metal loads in faecal sludge in Phnom Penh are presented in Table 2. As seen for chemical parameters, the concentrations of the different heavy metals analysed (classified into two groups, essential and non-essential metals) also showed high variation, non-normal distribution and large standard deviation (almost equal to the mean value). Mean and median values were very different, but the mean concentration (±standard deviation) of all heavy metals analysed was generally higher in rainy-season than in dry-season samples. The concentration ranges (mg/kg TS) in dry season samples were: As 0.28–5.7, Cd < 1–2.3, Hg 1.1–16, Pb 1.4–17, Cr < 1–13, Cu15-680, Ni 2.5–57, Zn 810–1900, while those in rainy-season samples were: As 2.8–15, Cd < 1–2.2, Hg < 0.02–16, Pb 9.1–112, Cr 22–72, Cu 67–280, Ni 12–30, Zn 320–4300. The two metals present in the highest concentration were Zn and Cu in both seasons, while the two present in the lowest concentrations were As and Cd in both seasons. The concentrations of Pb and Cr were higher than those of Ni and Hg in rainy-season samples, while a trend for the reverse was observed in dry-season samples, where the Cr concentration was among the lowest recorded.

4. Discussion

The mean concentration of TN in faecal sludge samples in this study was higher than values reported in the literature (Eliyan et al., 2022b; Ahmed et al., 2019; Afolabi and Sohail, 2017). This discrepancy could derive from analytical errors arising when using spectrophotometric methods for TN analysis, e.g. from insufficient addition of oxidation reagent leading to organic and inorganic N remaining in samples after digestion owing to the high COD in faecal sludge samples. This interference could be the reason why NH$_4$–N was reported to be higher than TN in one study (Ahmed et al., 2019), when theoretically it should be lower, and why total Kjeldahl nitrogen (TKN) was higher than TN in another study (Afolabi and Sohail, 2017), when it should be lower than or equal to TN as nitrates are not detected in that method. A similar issue was found in a previous study in Phnom Penh (Eliyan et al., 2022b). However, the TN concentrations found in the present study were in line with previously reported values in a study of septic tank contents in Hanoi, Vietnam, and Kampala, Uganda (Englund et al., 2020) and in household pit latrine faecal sludge in Kampala, Uganda (Strande et al., 2018).

Significant differences in concentrations in faecal sludge between the

Table 3
Summary of mean values of all parameters in dry-season and rainy-season faecal sludge (FS) samples in this study and mean values from other studies, and permissible limits of heavy metal concentration in the Cambodian standard for organic fertiliser and other international standards and guidelines on use of biosolids for land application. Bold type indicate that a value exceeds either the Cambodian standard for organic fertiliser or the Swedish limit for compost, while bold and italics indicate that it exceeds both. All values are in mg/kg total solids (TS), unless otherwise indicated. Value after ± signs are standard deviation. (–) data not available. The grey shaded panel shows values from different standards and guidelines for comparison.

Parameter	This study	Mean heavy metal concentrations in other studies						Values from different standards and guidelines			
	Mean value from both seasons	FS in Nakuru, Kenya(1)	FS in peri-urban Ashanti region, Ghana(2)	FS in Limpopo, South Africa(3)	Dewatered FS in Kampala, Uganda(4)	Dry dewatered FS in Greater Accra region(5)	Wet dewatered FS in Greater Accra region(5)	Cambodia National standard for organic fertiliser(6)	Permissible limit for Compost in Sweden(7)	Council Directive 86/278 EEC(8)	USEPA Limits for EQ and PC Biosolids(9)
	Non-essential heavy metals										
As	3.6±3.0	-	0.152±0.027	-	-	**10.82±0.46**	**10.02±3.26**	10	-	-	41
Cd	<1[a]	2.3±0.1	0.045±0.005	0.32	0.9±0.4	0.60±0.11	0.86±0.04	5	3	20-40	39
Hg	***5.1±4.3***	-	-	-	-	-	-	0.15	3	16-25	17
Pb	29±28	13.9±1.2	0.160±0.053	17.96	73.3±29.9	6.69±1.10	18.77±1.45	100	150	750-1200	300
	Essential heavy metals										
Cr	23±22	42.4±4.3	-	44.13	46.9±36.2	42.53±6.23	26.33±11.94	50	150	-	1200
Cu	130±100	68.5±4.0	3.978±0.439	80.80	113.7±41.1	125.93±14.37	***185.30±3.24***	300	150	1000-1750	1500
Ni	20±12	-	-	18.89	15.3±6.8	25.12±4.05	22.04±1.82	50	50	300-400	420
Zn	***1 400±690***	51.6±4.8	2.235±0.102	303.83	448.7±151.9	**694±72.56**	**923.77±86.65**	1000	500	2500-4000	2800

[a] Median value. For abbreviations, see text. (1)(Moturi et al., 2018). (2)(Appiah-Effah et al., 2015), units mg/L. (3)(Shamuyarira & Gumbo, 2014). (4)(Manga et al., 2022). (5)(Ahmed et al., 2019). (6)(MAFF, 2012). (7)(Sharma et al., 2017). (8)(CD, 1986). (9)(USEPA, 1994)

dry and rainy seasons were detected for almost all metals analysed except Hg, Ni and Zn. In general, the concentration of all metals was higher in rainy-season samples than in samples collected in the dry seasons. One source of the greater heavy metal loads during the rainy season could be surface run-off during storm events. A previous study examining the levels of heavy metals in the Chan Thnal reservoir in Cambodia also concluded that the Cd, Cu, Zn and Pb concentrations were higher in the rainy season than in the dry season (Chheang et al., 2021). Higher loads of Cd during the rainy season have also been reported in a study in Eastern Cape province, South Africa (Agoro et al., 2020). However, all 42 samples collected in the present study were independent samples, so is difficult to compare the results obtained given the many possible influential variables, including types of containment systems, user habits and management practices. A study on pit latrine sludge in a peri-urban residential area of Zimbabwe found that user habits and management practices made each containment unique in terms of faecal sludge characteristics (Changara et al., 2018). Another factor that contributes significantly to the variation in physicochemical characteristics of faecal sludge in Phnom Penh is the type of wastewater captured by the containment systems (only blackwater or mixed household wastewater) (Eliyan et al., 2022b). Those factors were not assessed in the present study, but could contribute to the presence of heavy metal in faecal sludge and greywater is the main contributor of heavy metals (Vinnerås et al., 2006). In this study, sampling was conducted at disposal sites and the research team had only a limited time to talk to operators during emptying events, so their responses were not used. In any cities that have onsite containment units capturing mixture of domestic wastewater, there would also be a chance that faecal sludge contains higher concentration of heavy metal than the permissible limit to be used as fertiliser.

Heavy metal concentrations found in faecal sludge in different studies are generally low (Afolabi and Sohail, 2017), as confirmed in this study. The mean concentration of all metals in both seasons followed the order Zn > Cu > Pb > Cr > Ni > Hg > As > Cd (Table 3). A similar decreasing trend in heavy metal concentrations is reported in the literature, e.g. Zn was the most common element found in faecal sludge from peri-urban areas in the Ashanti region, Ghana (Appiah-Effah et al., 2015); from Limpopo, South Africa (Shamuyarira and Gumbo, 2014); from dewatered faecal sludge in Kampala, Uganda (Manga et al., 2022); and from wet and dry dewatered faecal sludge in the Greater Accra region, Ghana (Ahmed et al., 2019). However, a study on Cd, Pb, Cu and Zn concentrations in sewage sludge in Nakuru, Kenya, found that Cu was present in the highest concentrations, followed by Zn (Moturi et al., 2018).

Heavy metals are categorised as essential, i.e. required in the diet and with a biological use, e.g. in enzymes (Cr, Cu, Ni, Zn) and non-essential, i.e. toxic to organisms even in trace amounts (Slobodian et al., 2021) (As, Cd, Pb and Hg). However, exposure to high amounts of any heavy metal, whether essential or non-essential, can have adverse health effects (Slobodian et al., 2021; Vinnerås et al., 2006). In general, the level in human excreta per person per day is: Zn 9–16 mg, Cu 1.4–1.5 mg, Ni 0.3 mg, Cd 0.02–0.03 mg, Pb 0.07–0.14 and Hg 0.01 mg (Schouw et al., 2002). The concentrations mainly reflect the use of the different metals in society, with some local deviation due to background content in the environment, e. g As from the groundwater. The major contributor of Cd could be the use of Cd in rubber tyres and heavy traffic, from where Cd can enter stormwater drains and run-off from nearby roads (Agoro et al., 2020; Shamuyarira and Gumbo, 2014). Phnom Penh is a city with heavy traffic on the roads and generating Cd-contaminated stormwater that enters the urban drainage system. During the rainy season and especially during severe storm events, the city is flooded and overflows of stormwater possibly enter faecal sludge containment systems. It has been reported that around 77% of residents in Phnom Penh have their faecal sludge containment unit emptied in the rainy season, when it probably becomes visibly full due to backflow or overflow (PPCA, 2021). Other non-essential metals such as As are found in groundwater in the study region, with peri-urban areas of Phnom Penh being As risk areas. A groundwater study by UNICEF and other collaborating agencies revealed that these high concentrations of As in groundwater are strongly associated with the floodplains of the Bassac, Mekong and Tonle Sap rivers (Berg et al., 2007). The source of Hg could potentially be use of Hg-containing batteries in households and amalgam in dentistry. Dental amalgam (via teeth brushing and defecation) contributes more than 80% of Hg in domestic wastewater, while other possible sources of Hg contamination are common household and toiletry products (Friedler et al., 2019). In addition to the diet, Cu can also derive from other sources, such as corrosion of water pipes. Zinc is a constituent of galvanised steel, which is used in pipes in the drinking water distribution network, so piped water supply could be contaminated with Cu and Zn. Use of cleaning materials containing Cu and Zn is another possible source. A main source of Zn and Cu is in-house plumbing and greywater, which contribute 90% of the total metal load (Friedler et al., 2019). Household effluent such as greywater may contribute strongly to the total heavy metal content in faecal sludge (WHO, 2006).

Different sources contribute to the higher concentration of heavy metals in Phnom Penh and pose a concern that would limit the reuse potential of faecal sludge. Such concerns could possibly be relevant for other cities in similar context. For instance, any cities that face with frequent flooding, have onsite containment units connected to urban drainage network and have water based toilets connected to containment units. It is important to identify all sources of pollutants in order to implement measure upstream to limit heavy metal loads entering wastewater, because once the heavy metals are present in wastewater they are costly and difficult to remove and pose serious health issues.

Cambodia divides fertilisers into five different types, based on the nutrient and micronutrient content. These are: inorganic or chemical fertiliser, organic fertiliser, bio-fertiliser, soil conditioner and raw material. The classification is based on the primary nutrient (N, P, K) content in normal inorganic fertiliser (MAFF, 2012). Almost all individual heavy metal concentrations in the faecal sludge samples analysed in the present study were below the permissible limits in the Cambodia standard for organic fertiliser and the Swedish limits for compost (Sharma et al., 2017), with the exception of Hg and Zn (Table 3). There is currently no standard limit for total heavy metal load in faecal sludge in Cambodia, but all samples analysed fell within the acceptable range in biosolids based on the USEPA limits for exceptional quality for land application and the EU standard for sludge for use in agriculture (USEPA, 1994; CD, 1986).

Given the high concentrations of Hg and Zn in faecal sludge, exceeding the Cambodian standard for organic fertiliser, treated faecal sludge biosolids should only be used as a soil conditioner and not as a complete substitute for fertiliser, meaning that it should only be applied to some selected crops or applied only in limited amounts. To ensure safe reuse, further studies should seek to identify crops that may not absorb heavy metals, especially As, Pb, Ni and Zn, and to determine the amount of faecal sludge that may be safe to apply considering the amount of plant nutrients needed and heavy metal accumulation in soil and uptake by plants. Alternatively, treated faecal sludge should be used as fertiliser in soil production for non-edible plants such as grass and flowers in Phnom Penh and nearby city parks.

Another alternative could be to introduce a source separation system for faeces and urine. This would be beneficial for biological treatment (Rose et al., 2015), given the high nutrient content in urine and greater heavy metal load in faeces (Schouw et al., 2002). Urine is the highest contributor of nutrients to domestic wastewater (79% of N, 47% of P) and greywater is the lowest (Friedler et al., 2019). Most heavy metals in domestic wastewater (e.g. Zn, Cu, Ni, Cd, Pb, and Hg) derive from faeces (Vinnerås et al., 2006; Schouw et al., 2002). Therefore, urine is the most valuable resource that can be recovered from domestic wastewater.

The concentration of heavy metals in recycled fertiliser needs to be set in relation to the benefits of the fertiliser, since otherwise there is a risk of just diluting a polluted fertiliser with a clean material for

Table 4

Summary statistics on concentrations (mg/kg phosphorus (P)) of heavy metals in faecal sludge in this study and in other waste materials. Bold indicates that the value exceeds the average level in mineral P fertiliser. (−) not included/data not available. Grey shaded column shows mean heavy metal concentrations in mineral fertiliser samples in 12 European countries.

Parameter	This study(1)					Fresh urine(2)	Faeces(3)	Urine+faeces mixed(3)	Farmyard manure(3)	Sewage sludge(4)	Mineral P fertiliser(5)
	Min	Max	Mean	Median	SD						
Non-essential heavy metals											
As	11	1 200	**170**	120	280	-	-	-	-	-	123
Cd	12	140	57	45	40	0.7	20	7	16	46.9	82.7
Hg	43	1 200	410	260	350	1	-	-	-	-	-
Pb	58	2 100	**860**	**810**	620	2	40	15	**124**	**1108**	55.3
Essential heavy metals											
Cr	20	1 300	390	340	360	10	40	20	463	1 072	1100
Cu	370	60 000	10 000	5 400	13 000	101	2186	797	3537	13 360	-
Ni	100	7 700	**1800**	**1 500**	2000	7	148	54	**427**	**617**	190
Zn	20 000	360 000	**111 000**	**89 000**	80 000	45	**21 312**	**7 146**	**18 049**	**19 793**	2 290

(1)Faecal sludge density 1.001 kg/m3 (Radford & Sugden, 2014). (2)(Vinnerås et al., 2006). (3)(Jönsson et al., 2004); farmyard manure from organic cattle farms in Sweden. (4)(WHO, 2006). (5)Mineral fertiliser samples in 12 European countries (n = 196) (Nziguheba & Smolders, 2008)

recycling. The most simple correlation is to refer to the fertiliser value, e.g. mg heavy metal/kg P recovered. For sustainable fertiliser production, introduction of new heavy metals into the food cycle should be avoided as much as possible. The concentration of heavy metals in faecal sludge in this study and in other types of waste material in relation to the recovered P is shown in Table 4. The mean concentrations of As, Pb, Ni and Zn in faecal sludge were higher than in other waste sources and in mineral P fertiliser (Nziguheba and Smolders, 2008; WHO, 2006; Jönsson et al., 2004). However, if median concentration were used for the comparison, only Pb, Ni and Zn concentration in faecal sludge were higher than in other waste materials and in mineral P fertiliser. Farmyard manure and sewage sludge had higher Pb, Ni and Zn loads than mineral P fertiliser, while faeces and mixtures of urine and faeces had higher Zn loads. Fresh urine was the only waste fraction with lower reported heavy metal concentrations in relation to P recovered than mineral P fertiliser (Table 4). When recycling faecal sludge, it is therefore important to keep heavy metal concentrations as low as possible by reducing non-food related heavy metal loads entering the faecal sludge management system. Implementation of upstream prevention would require collaboration with stakeholders in other sectors that are the main contributors of heavy metals. In the specific case of Phnom Penh, transportation, stormwater runoff and use of household products likely contribute to heavy metal contamination of faecal sludge, but further studies are needed to identify the key contributors.

5. Conclusions

Heavy metal concentrations in faecal sludge samples collected in Phnom Penh were significantly higher in the rainy season than in the dry season, probably due to metal-containing inflow from stormwater drains and run-off from roads during the rainy season. Based on heavy metal load in relation to P recovered the sludge cannot be recommended to be used as fertiliser in agriculture. This present study also revealed that there is a potential of heavy metals contamination in faecal sludge in any settings that have similar context like Phnom Penh, therefore direct use of treated faecal sludge biosolids from such settings as fertiliser should be avoided to safeguard public health.

Since treated faecal sludge as biosolids would not be safe to be used as fertiliser in agriculture, sanitation stakeholders should consider different alternatives for closing nutrient loops, such as: i) source separation and reuse of different household wastewater fractions; ii) pollution prevention at upstream sources; and iii) use of biosolids as a soil conditioner together with other fertiliser for selected crops. As a short-term solution to the current lack of faecal sludge management in Phnom Penh, use of biosolids as a soil conditioner with other fertiliser or for soil production is a good alternative.

To ensure safe reuse, future studies should identify crop types that do not absorb heavy metals and suitable faecal sludge treatment methods for Phnom Penh and other cities with similar settings. In a long term planning, potential for implementation of upstream source prevention and source separation should be further investigated since both options would have greater benefits, but also demand greater commitment and more efforts from all stakeholders to ensure successful and sustainable faecal sludge management, and thus safely managed sanitation services in Phnom Penh. Nevertheless, future research on technologies for heavy metals removal from faecal sludge should be conducted, thus making treated faecal sludge biosolids safe to be used as fertiliser.

CRediT authorship contribution statement

Chea Eliyan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jennifer McConville:** Conceptualization, Investigation, Validation, Methodology, Supervision, Writing – review & editing. **Christian Zurbrügg:** Methodology, Supervision. **Thammarat Koottatep:** Methodology, Supervision, Writing – review & editing. **Kok Sothea:** Funding acquisition, Methodology, Supervision. **Björn Vinnerås:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All relevant data are included in the paper.

Acknowledgments

This work would have not been successfully conducted without financial support from the Swedish International Development Cooperation Agency through “Sweden-Royal University of Phnom Penh Bilateral program” [Contribution Number: 11599]. The authors thank Claudia von Brömssen for statistical support during study design and data analysis. Special thanks to all staff at Boeung Trabek pumping station for their help during faecal sludge sampling and to all emptying and transportation operators for providing faecal sludge samples.

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Environmental Technology & Innovation 32 (2023) 103384

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Sustainability assessment of faecal sludge treatment technologies for resource recovery in Phnom Penh, Cambodia

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ARTICLE INFO

Keywords:
Low-income country
Nutrient recovery
Onsite sanitation
Resource-oriented sanitation
Sustainable sanitation
Treatment product

ABSTRACT

Selection of appropriate sustainable treatment technologies involves satisfying user requirements, quality standards on treatment and products, and specific socio-technical constraints in the intended context. Using locally adapted multi-criteria assessment (MCA), this study investigated faecal sludge treatment technologies that enable resource recovery in Phnom Penh. A four-step structured approach was applied, involving i) identification of available options, ii) prerequisite screening, iii) MCA and iv) stakeholder discussions and ranking. Data were collected in a literature review, stakeholder interviews and an online survey. Lists of suitable primary (n = 7) and secondary (n = 13) treatment technologies were compiled based on the literature. Four secondary treatment technologies (solar drying, co-composting, vermicomposting, black soldier fly larvae (BSFL) composting) were retained after prerequisite screening and subjected to MCA. Co-composting was ranked highest in MCA, since it performed well in multiple aspects, especially for health criteria. However, when economic return on investment was prioritised and a lower treatment class was accepted, e.g. USEPA Class B biosolids, the highest ranking was achieved by vermicomposting or BSFL composting. If institutional criteria were included in the assessment, solar drying would likely be the highest-ranked option, since this simple technology requires less logistically complex stakeholder arrangements than co-composting. These results show that the ranking obtained for different sludge treatment options depends on criteria weighting and trade-offs. Considering secondary treatment options is crucial during early planning for faecal sludge management in a city of low-and-middle income countries, as the primary treatment must yield appropriate feedstock quality for the secondary treatment step.

1. Introduction

Increasing sanitation coverage or the number of toilets in communities should not be seen as a stand-alone solution for safely and

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https://doi.org/10.1016/j.eti.2023.103384
Received 20 July 2023; Received in revised form 7 September 2023; Accepted 29 September 2023

sustainably managed sanitation, which should consider the management of the entire service chain (Spuhler et al., 2018). The sanitation service chain includes user interface/containment, emptying/collection, conveyance, treatment and end use/disposal (Tayler, 2018). When designing sustainable sanitation service chains, care should be taken to ensure that they are socially acceptable and technically and institutionally appropriate, while also protecting the environment, human health and natural resources (Andersson et al., 2016; SuSanA, 2008; WHO, 2006). Among these, health protection should be considered the most crucial requirement in terms of the overall sanitation objective and reuse of end-products from faecal sludge recovery (McConville et al., 2020a). Selection of treatment technologies also depends on user requirements and context-specific health, environment, economic, socio-demographic and institutional conditions (Spuhler et al., 2018). Successful implementation of sustainable sanitation systems can be achieved only if the local situation is taken into account (Semiyaga et al., 2015; Katukiza et al., 2010). Stakeholder consultation is a critical step to ensure that the treatment option selected accounts for the local specific context and meets sustainability criteria (McConville et al., 2020a). However, such assessments generally require extensive data and data availability is often poor in low- and middle-income countries (Benavides et al., 2019).

Many cities in low- and middle-income countries are struggling to provide sustainable faecal sludge management services, due to rapid urbanisation, population growth and generation of enormous quantities of faecal sludge. At the current rate of progress, the world will only reach 67% coverage of safely managed sanitation by 2030 (WHO and UNICEF, 2021). Onsite sanitation systems serve around 29% of the urban population globally and coverage is expected to double by 2030 (WHO and UNICEF, 2017; Strande, 2014). Faecal sludge is not safely managed in many developing countries, e.g. the contents of onsite containment units often end up being dumped in the environment near the point of generation (Cofie et al., 2016). A review of studies conducted in 12 cities in Asia reported that only 37% of faecal sludge generated from onsite sanitation systems was safely managed (Peal et al., 2015). For example, untreated faecal sludge in Phnom Penh, Cambodia, often ends up in open channels or residential environments (PPCA, 2021). Unsafe disposal of faecal sludge from onsite sanitation systems can have detrimental impacts on public health and the environment (Krueger et al., 2020). The heavy load of pathogens from faecal sludge poses human health risks, while nutrient discharge causes eutrophication of surface waters and pollution of groundwater (Singh et al., 2017; Katukiza et al., 2010). Therefore, it is crucial to find a workable solution for faecal sludge treatment and management that offers a viable alternative to indiscriminate and illegal dumping and can recover resources (Krueger et al., 2020).

There is a growing paradigm shift to viewing human waste as a resource, rather than a problem (Tayler, 2018). The environment would then be protected and resources saved (Semiyaga et al., 2015). In addition, economic value of faecal sludge end-products could incentivise more appropriate and viable faecal sludge management (Zewde et al., 2021; Rao et al., 2017; Semiyaga et al., 2015; Diener et al., 2014). Different types of resources can be recovered from faecal sludge treatment systems, such as energy (solid/liquid fuel and electricity), insects as protein for animal feed, building materials, fertiliser/soil conditioner and water (Andriessen et al., 2019; Schoebitz et al., 2016; Gold et al., 2015; Semiyaga et al., 2015; Diener et al., 2014). Unfortunately, few of the potential resources contained in wastewater and sludge in low-income countries are recovered in a safe manner, while the majority remain untreated or are used informally (unregulated) (Drechsel et al., 2015). Improper use and disposal of faecal sludge is a challenge for many cities globally (Zewde et al., 2021), including Phnom Penh. Therefore, there is a need for guidance on the performance of technologies for faecal sludge treatment and structured support for planning faecal sludge management in locally adapted ways.

The aim of this study was to support decision-making by city sanitation planners on faecal sludge management in a low-income urban context. This was done by comparing locally appropriate faecal sludge treatment technologies enabling potential resource recovery, which could minimise exposure to faecal sludge contaminants and indiscriminate disposal within neighbourhoods and the environment, using Phnom Penh as a case study. Specific objectives of the study were to: 1) characterise treatment technologies; 2)

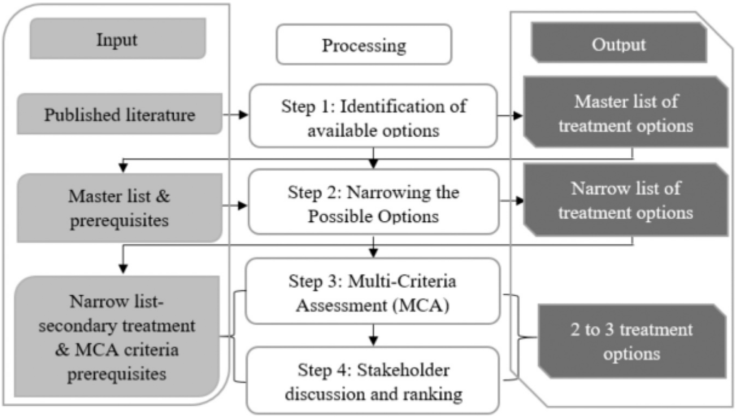

Fig. 1. Flow chart of the four-step structured approach applied in this study for ranking sustainable faecal sludge treatment technologies. The output from steps 1 and 2 was used as input to the next step. Steps 3 and 4 were performed in parallel and the same inputs were used for both.

conduct an in-depth assessment of locally adapted treatment technologies; and 3) develop a structured approach to support planning for faecal sludge management. Treatment technologies were assessed in terms of multiple criteria (health, environment, economic, socio-technical, institutional) using a structured approach that combined prerequisite screening, multi-criteria assessment (MCA), and weighing and ranking by stakeholders.

2. Methods

A four-step structured approach was used to identify options and assess these based on locally relevant criteria in MCA (Fig. 1). This four-step approach was complemented with stakeholder input through interviews with sanitation sector representatives, a structured questionnaire and an online survey on public acceptance of faecal sludge treatment products. The methodology is described in detail below.

2.1. Study area

The selected study area was Phnom Penh, the capital city of Cambodia, 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 total land area of Phnom Penh is 679 km^2, divided into 14 districts (five urban, nine peri-urban) with a total population of approximately 2.28 million (around 500,000 households) (NIS,

Table 1
List of sustainability indicators and respective sub-indicators used for multi-criteria assessment (MCA) scoring of faecal sludge secondary treatment options.

Indicator	Units	Sub-indicator used this study	Stakeholder-identified indicator	Data sources
Health criteria				
Sanitisation efficiency of the treatment	Log reduction	Total coliforms/E-coli	Quality of end-product according to WHO guidelines	Literature review
		Faecal streptococci/ enterococcus	Ensuring safe reuse of end-product	
		Helminth eggs		
Environmental criteria				
Energy requirement	kWh/ton	Potential energy demand by treatment system	-	Adapted from literature review
Area requirement	kg TS/m^2/year	Total land area require to operate the system	Space requirement	
Climate impact	g/kg feedstock	GHG emissions from the treatment system	-	
Economic criteria				
Investment cost	Qualitative	Expected total investment cost compared to planted drying bed system	Capital cost (CAPEX)	Literature review and our own expert judgement
Operation and maintenance (O&M)		Expected daily O&M cost compared with planted drying bed system	Operating cost (OPEX)	
			Depreciation cost of the system	
			Reliability of support/fund	
End-product value	$/ton	Value of treatment end product based on local classification	Cost of recovered product	
			Market size of reuse/ fertiliser product	
Socio-technical criteria				
Robustness of technology	Qualitative	Level of technology development	Treatment efficiency	Literature review
		Capacity to endure shock load-quality of input material		
		Capacity to endure shock load-quantity of input material		
		Resilience to climate change impact-flooding		
Public acceptance of treatment end products	% of acceptance	Public acceptance of treatment end-product to grow inedible plants, trees and grass	Acceptability of treatment end- product by farmers	Online survey questionnaire
		Public acceptance of treatment end-product to grow food for animals	Potential buyers	
		Public acceptance of treatment end-product to grow food for humans		
Institutional criteria				
Technical capacity	Qualitative	Capacity to carry out technical service-delivery and logistical tasks mandated within the sanitation service chain	Legal framework on safe reuse	Field data through interviews with sanitation stakeholders
Adaptive capacity		Capacity to adapt and self-renew to implement mandated duties in the sanitation service chain	Public private partnership	
Capacity to attract external resources		Capacity to relate and attract resources and support to carry out mandated duties		

2020). Approximately, 85% of the population rely on onsite sanitation and containment units that are connected to an urban sewage network where possible (Frenoux and Tsitsikalis, 2015; Frenoux et al., 2011; PPCA, 2021), while around 15% are directly connected to urban sewers or open channels (PPCA, 2021). About 71% of onsite sanitation residents have their containment connected to urban sewage network (Eliyan et al., 2022a). However, with rapid urban development, the city has been unable to extend the urban drainage network to newly developed areas, so households living in those areas are unconnected to the sewage network. Two types of onsite containment system are used in the city, cesspits and septic tanks. Cesspits are the dominant system, serving up to 93% of the total population, and when household cesspits are full or clogged, mechanical emptying is performed (Eliyan et al., 2022a). The sludge removed is transported to disposal sites or dumped in the open environment, since there is currently no faecal sludge treatment plant available (Eliyan et al., 2022a; PPCA, 2021). Piped water supply is the main source of water supply for residents in Phnom Penh, serving up to 93% of population (PPCA, 2021).

Phnom Penh still uses combined drainage system that transports all types of wastewater, including stormwater during storm events (Frenoux et al., 2011). Two main wetlands (Cheung Ek with surface area changes between 13–20 km^2 from dry to rainy season and Kob Srov with surface area of around 32 km^2) surround the city and play a key role in treating the combined wastewater before being discharging to final recipient water bodies (Mekong and Tonle Sap). However, the two wetland areas are shrinking and being filled with earth to reclaim land (Doyle, 2013; Irvine et al., 2015; RGC, 2016). Flooding occurs several times in rainy season every year in newly urbanized and insufficient drainage facilities installed areas (JICA, 2016). Increased pump capacity at the Trabek and Tumpun stations could be an option to reduce the volume and duration of surface flooding in southern part of the city (Irvine et al., 2015).

2.2. Sustainability criteria

Sustainability criteria were selected based on sustainable sanitation and wastewater management as defined by Andersson et al. (2016) and criteria used for decision making on nutrient recovery from faecal sludge in Uganda (McConville et al., 2020a). The five types of criteria employed in sustainability assessments in this study were: i) health; ii) environmental; iii) economic; iv) socio-technical; and v) institutional. Indicators and sub-indicators for these criteria (Table 1) were developed through a literature review and our own expert judgement, to ensure a transparent assessment and scoring process.

Many environmental indicators were considered for inclusion in the assessment. Some, such as eutrophication potential, groundwater pollution and generation of unused by-products, were excluded since they were considered non-relevant for the specific context or since insufficient data were available. For instance, eutrophication potential is applicable when wastewater and effluent from supernatant treatment technologies are discharged into water bodies. In this study, it was assumed that water from sludge dewatering would be treated at a wastewater treatment plant and this option was therefore excluded. The risk of groundwater pollution was excluded due to lack of available data to quantify this indicator. However, these indicators might be relevant for other studies or assessments.

Sub-indicators identified by sanitation sector stakeholders (Table 1) were matched to types (i-v) identified from the literature by clustering. For example, treatment efficiency was taken as the ability of the technology to function properly (i.e. achieve design treatment levels) in various testing circumstances, e.g. shock loading, and was thus considered as a social-technical rather than environmental criterion. Some stakeholder sub-indicators, such as depreciation cost, market size and source of funding, were not included, since no data were available to compare these for each system assessed. Instead of considering the acceptability of treatment end-products to farmers, the MCA included public acceptance as one of the sub-indicators, since the public are the final food consumers and if they show public acceptance farmers may also be willing to do so. There was also a challenge in including farmers' perceptions, since they may lack knowledge of different treatment end-products.

2.3. Stakeholder input

Stakeholder interviews with sanitation sector representatives were designed to collect information on their opinions, knowledge and capacity in their current mandate to manage faecal sludge systems and treatment technologies in Phnom Penh. The stakeholders contacted for interview included actors in the public and private sectors and non-government organisations (NGOs), who were identified based on their official role in the sanitation sector in Phnom Penh. A structured questionnaire with open-ended questions (see Supplementary Information (SI) Part I) was developed to facilitate the interview sessions with different stakeholders. This questionnaire covered aspects of vision, core mission and current mandate in relation to the sanitation sector and faecal sludge management and the stakeholders' knowledge of multiple aspects (health, environmental, economic, socio-technical, institutional). Stakeholders were also asked to identify key indicators/sub-indicators that they considered relevant for the MCA. The initial plan was to assess institutional capacity through certain questions (see SI Part I), but to avoid bias in the scoring this part was excluded since the stakeholders lacked background knowledge of certain treatment technologies. The institutional criteria were therefore only included for final ranking of the treatment technologies after scoring. Among the institutional criteria, stakeholders suggested inclusion in the assessment of a legal framework on safe reuse and public-private partnership, but we decided to exclude this because a legal framework on safe reuse partly related to aspects already included in the health criteria (sanitisation efficiency of the treatment). Additionally, the standards set for organic fertiliser in Cambodia (MAFF, 2012) focus on end-product quality, and not on technologies or processes used to produce the end-product, so scoring using this sub-indicator would likely result in the same value for all technologies. Similarly, faecal sludge management is rather new in Cambodia, so scoring for the public-private partnership sub-indicator would likely give the same value for all since there is no baseline information available.

Sustainability in sanitation can only be achieved by taking into account the local situation (Katukiza et al., 2010). Involving sector stakeholders in discussions and including their perspectives is a way to ensure that local inputs and locally sustainability criteria are included (McConville et al., 2020a). Most of the criteria suggested by sector stakeholders in this study were found to be similar to existing sub-indicators identified from the literature (Table 1).

2.4. The four-step structured approach

The four-step structured approach described in McConville et al. (2020a) was employed, with some modifications in each step, to identify treatment alternatives enabling resource recovery in the case of Phnom Penh (Fig. 1). The approach involved i) identifying available options for treating faecal sludge; ii) narrowing down the options in screening based on a set of locally adapted prerequisites; iii) MCA; and iv) stakeholder discussions on sustainability criteria. In MCA of the technologies, published literature was used when local field data were not available. An online survey of stakeholders was used in the MCA and ranking (steps 3 & 4).

2.4.1. Step 1: Identifying available options

A review was conducted of published literature on faecal sludge and wastewater treatment technologies that could be used to treat faecal sludge removed from sanitation systems, regardless of their feasibility of implementation in Phnom Penh (McConville et al., 2020a; Harder et al., 2019; Tayler, 2018; Singh et al., 2017; Nikiema et al., 2014; Strande et al., 2014). Faecal sludge treatment technologies generally consist of at least two treatment steps, so step 1 in the approach of McConville et al. (2020a) was modified to include primary and secondary treatments, resulting in lists of possible primary and secondary faecal sludge treatment technologies, respectively, that were classified and summarised based on: a) type of process (physical, chemical, biological or thermal); b) possible input materials (raw faecal sludge, dewatered faecal sludge or supernatant); and c) outputs.

2.4.2. Step 2: Narrowing possible options

Prerequisite screening was performed before moving to the MCA step, in order to eliminate non-feasible technologies based on a set of locally appropriate criteria. The three screening prerequisites for primary treatment technologies were: 1) use of chemicals; 2) energy requirements; and 3) process complexity. Reuse potential of end-products was included as a fourth criterion when screening secondary treatment technologies. These prerequisites were selected because chemicals and energy (both mostly imported) are costly in Cambodia. There is also limited skilled labour to operate highly complicated systems in the sanitation sector. Selection of prerequisites focused on technical aspects of treatment technologies, other aspects such as health and environmental protection were included in MCA scoring step. In comparisons based on published data, each treatment technology was scored high, medium, or low (none) for each screening prerequisite. Treatment technologies with high use of chemicals, high energy requirement, high process complexity or low reuse potential were not investigated further. Reuse potential refers to the possibility to generate end-products from the treatment technology that can be reused either as energy, nutrient recovery or both. The pre-requisite assessment and the final decision on elimination of non-feasible treatment technologies was based on the information available and our expert judgment.

2.4.3. Step 3: Multi-criteria assessment (MCA)

MCA was applied only for secondary treatment options, since any decision on primary treatment technology depended on the secondary process used. The MCA started by defining locally appropriate sustainability criteria to assess the feasibility of implementing the narrow shortlist of secondary treatment technologies.

Some prerequisites were also included, since they were considered important decision-making factors and since MCA allows for quantitative comparison. For instance, technologies with either low or medium energy requirement were included in the MCA, although it is important how much energy each treatment system requires. Similarly, technologies with either high or medium reuse potential in prerequisite screening were included in the quantitative assessment, using end-product value was an indicator to assess performance. Process complexity in prerequisite screening was represented by the robustness of technology indicator in MCA, although the robustness level included technology readiness level and the technology's capacity to endure shock loads of both quality and quantity of feedstock.

The sub-indicators used to assess the shortlisted technologies were scored based on literature reviews, stakeholder interviews, online surveys and our own expert judgement. Specifically, sub-indicators of the health, environmental, economic and socio-technical (robustness of technology indicator) criteria were scored according to the performance of each technology based on findings in the literature adapted to Phnom Penh as the case study (for full details, see SI).

A Likert scale of 1–5 (where 1 is the lowest ranking and 5 the highest) was applied when scoring each sub-indicator in MCA (see Table 1). For ease of understanding, traffic light colours were also used. For some indicators that could not be scored in detail (1–5), a three-point scale was applied (1, 3, and 5, corresponding to red, amber and dark green, respectively) (see SI for full details of evaluation and scoring of each technology).

2.4.3.1. Health. Regarding health aspects, different types of pathogens were considered, since pathogen removal efficiency varies between organisms and treatment technologies. For example, helminths can survive longer in the environment and are therefore most difficult to remove in most technologies (WHO, 2006). The scoring criteria for health were based on different degrees of pathogen inactivation in comparison with recommended World Health Organization guidelines (WHO, 2006), United State Environmental Protection Agency (USEPA) Part 503 rules on the use of Class A/Class B biosolids in agriculture (USEPA, 1994), and the standards set for organic fertiliser in Cambodia (MAFF, 2012).

2.4.3.2. Environmental. The indicators for environmental criteria included energy requirement (kWh/ton of feedstock), area requirement (kg total solids (TS)/m^2/year) and climate impact (GHG emissions in kg $CO_{2\ eq.}$/ton wet weight of feedstock) of each treatment technology. The assessment was based solely on technology performance reported in the literature, with adaptation to Phnom Penh. Scoring of the environmental indicators was weighted against the planted drying bed, the first faecal sludge treatment plant in Phnom Penh (currently under construction) (PPCA, 2021), but applying the reference baseline of GHG emissions from sludge treatment in reed beds in Hadsten, Denmark (Uggetti et al., 2012). To our knowledge, data on GHG emissions from planted drying beds are lacking and the reed bed is rather a similar system.

2.4.3.3. Economic. For the economic criteria, investment in a planted drying bed and its operation and maintenance (O&M) costs were used as the baseline cost to which other technologies were compared. The baseline value used was the total cost, including project management and operation, of the faecal sludge treatment plant under construction in Phnom Penh (PPCA, 2021). This baseline cost might differ in a different setting, time span or inflation context.

2.4.3.4. Socio-technical. Assessment of socio-technical criteria was based on technical robustness and public acceptance of the end-products. Robustness focused on level of technology readiness and resilience of the technology in different situations. A number of technologies are available for faecal sludge treatment, but their operational readiness and research are currently at different levels (Strande et al., 2014). In this study, we employed three technology development levels, established, transferring and innovative, where technologies in the established level had been used to treat faecal sludge (at least at pilot scale), technologies in the transferring stage had been used to treat wastewater, sewage sludge or other type of effluent and might be transferable to faecal sludge treatment, and technologies at the innovative stage were described only in laboratory-scale research. The established and transferring technologies have been applied for many years and much knowledge is available on their design, operation and maintenance.

Public acceptance of treatment end-products was assessed in an online survey (SI Part II) that was sent electronically to known contacts, who were asked to forward it to their respective networks. The response time was set at two weeks, during which a reminder was sent every other day to increase the number and range of respondents. This created a risk of bias, since most respondents were working in the education sector, in undergraduate or postgraduate programmes, and were therefore not representative of the general public in Cambodia. In total, 404 responses were obtained. Microsoft Excel 2010 was used for data handling and R software version 4.0.4 for data analysis. For the five-point Likert scale questions, the responses were combined into sub-scales and coded using the mean score (≤ 3 = non-acceptance, >3 = acceptance). Descriptive statistics tools such as total sum and percentage were employed to analyse the survey data and compare different levels of public acceptance.

2.4.4. Step 4: Stakeholder discussions and ranking

A key step in decision-making is selection of stakeholders and their participation in discussions. In this study, stakeholder input was used to weight the criteria in MCA, based on the criteria that stakeholders deemed most important. The sanitation sector stakeholder group was divided into two sub-groups: i) public stakeholders ($n = 5$) and ii) NGOs and development partners ($n = 8$). The public stakeholders comprised government officials, at either local level within Phnom Penh or national level. Subsequent stakeholder discussions involved the same group of people that provided stakeholder input.

Stakeholder weighing of the sustainability indicators was raised in the discussions in order to determine the level of significance of each sustainability indicator for stakeholders selecting a treatment technology for faecal sludge. The final ranking of the technologies was based on total score obtained from MCA and the weighing of the indicators by the sanitation sector stakeholders during interviews. Scoring for sustainability indicators was normalised using the equation $F = \left[\sum_{i=1}^{n}\left(\frac{ai}{c}\right)\right]x \quad G$ (Katukiza et al., 2010), where F is the

Table 2
Results of prerequisite screening of primary faecal sludge treatment technologies. Non-feasible technologies excluded from further assessment are shown in shaded boxes.

Process group	Treatment technology	Prerequisites			References
		Use of chemicals	Energy requirement	Process complexity	
Physical	Drying bed*	No	Low	Low	(Tayler, 2018; Singh *et al.*, 2017; Strande *et al.*, 2014)
Physical	Centrifugation	No	High	High	(Strande *et al.*, 2014)
Physical	Settling-thickening tank	No	Low	Low	(Singh *et al.*, 2017; Strande *et al.*, 2014)
Physical	Imhoff tank	No	Low	High	(Singh *et al.*, 2017)
Physical	Geobags	No	Low	Medium	(Tayler, 2018; Singh *et al.*, 2017)
Chemical	Coagulation and flocculation	High	Low	High	(Strande *et al.*, 2014)
Chemical	Conditioning	High	Low	High	(Strande *et al.*, 2014)

*Unplanted or planted.

normalised score of the sustainability indicator, n is the number of sub-indicators defining the criteria for the sustainability indicator, a is the average score of a sub-indicator for each sustainability indicator, c is the total of the average score of sustainability indicator and G is the average weighed score for sustainability indicators given by the stakeholders. The sum of normalised score (F) for all sustainability indicators was the total final score for a secondary technology option in the assessment, and determined its final ranking.

3. Results

3.1. Technologies reviewed

Selection of treatment option depends on various factors, the most important being the solids content of faecal sludge for primary treatment, whereas secondary treatment depends upon the reuse application (Tayler, 2018). Primary and secondary treatment technologies were both assessed in this study, since in most cases secondary technologies receive the dewatered sludge from primary technologies. The seven primary technologies (Table 2) and 13 secondary technologies (Table 3) identified in step 1 are presented in detail in Tables S1 and S2 in SI. Note that dewatered sludge and supernatant, the two most common products from primary treatment steps, require further treatment for safe reuse in agriculture or disposal purposes (Tayler, 2018). Supernatant is a liquid fraction from

Table 3
Results of prerequisite screening of secondary faecal sludge treatment technologies. Non-feasible technologies excluded from further assessment are shown in shaded boxes.

Process group	Treatment technology	Prerequisites				References
		Use of chemicals	Energy requirement	Process complexity	Reuse Potential	
Thermal	Pelleting	No	High	High	High	(Gold *et al.*, 2015)
Thermo-chemical	Pyrolysis	No	High	Medium	High	(Gold *et al.*, 2018; Gold *et al.*, 2015)
Thermal	Hydrothermal carbonisation	No	High	High	High	(Harder *et al.*, 2019) (Gold *et al.*, 2015)
Physical	Drying bed (solar drying)	No	Low	Medium	High	(Singh *et al.*, 2017)
Biological	Co-composting	No	Low	Medium	High	(Singh *et al.*, 2017)
Biological	Deep row entrenchment	No	Low	Medium	Low	(Singh *et al.*, 2017)
Biological	Vermicomposting	No	Low	Medium	High	(Singh *et al.*, 2017)
Biological	Anaerobic digestion	No	Low	High	Medium	(Singh *et al.*, 2017)
Biological	Black soldier fly larvae composting	No	Low	Medium	High	(Singh *et al.*, 2017; Strande *et al.*, 2014)
Biological	Co-treatment in waste stabilisation ponds	No	Low	Medium	Low	(Strande *et al.*, 2014)
Chemical	Ammonia treatment	High	Low	Medium	Medium	(Strande *et al.*, 2014)
Chemical	Alkaline stabilisation	High	Low	Medium	High	(Strande *et al.*, 2014)
Chemical	Oxidation	High	Low	High	High	(Strande *et al.*, 2014)

(Gold et al., 2018).

primary treatment of faecal sludge and is also generated from onsite sanitation containment units connected to the urban drainage network, which is the case for any household located within the drainage network coverage area (Eliyan et al., 2022b). The liquid fraction from both onsite containment units and faecal sludge could be treated at a domestic wastewater treatment plant, while the dewatered sludge could be treated with secondary treatment technologies depending on the reuse goals. Treatment of the liquid fraction was excluded from subsequent assessment in this study.

One person in Cambodia excretes on average 3.1 kg of N and 0.45 kg of P, annually. According to Swedish data, approximately 88% of N in excreta and 67% of P in excreta are found in urine and the rest are in faeces mainly in the solid fraction (Jönsson et al., 2004; Eliyan et al., 2022a). The main nutrient contributor is the liquid fraction passing the containment units and the faecal sludge is only contributing with a smaller amount of the total flow, approximately 10% of N and 20–30% of P.

3.2. Prerequisite screening results

After prerequisite screening to eliminate non-feasible treatment technologies, three primary treatment technologies and four secondary treatment technologies remained (Tables 2 and 3). The three primary treatment technologies were all physical processes: drying bed (unplanted or planted), settling-thickening tank and geobags. Further analysis and priority ranking of these technologies is needed before making a decision on their implementation, but was not performed in this study.

The four secondary treatment technologies that passed the screening step were drying bed (solar drying), co-composting, vermicomposting, and black soldier fly larvae (BSFL) composting. With the exception of solar drying, which can handle sludge with a lower TS content, the input material for those technologies should be dewatered sludge containing $>$ 20% TS (Tayler, 2018; Cofie et al., 2016; Nikiema et al., 2014) (see Table S2). Feedstock with a high TS content could be produced by the three primary treatments retained after screening (Table 2).

In the next assessment step, the four secondary treatment options shortlisted were compared in terms of their feasibility and applicability to handle the faecal sludge generated in Phnom Penh (and similar cities in developing countries). To facilitate the MCA, a specific type of each of these four secondary treatment technologies was defined as follows:

3.2.1. Drying bed (solar drying)

A treatment option to reduce the water content in sludge, the performance of which has been documented in studies using sludge from wastewater treatment plants (Stringel et al., 2019; Tayler, 2018; Strande et al., 2014). The technology is still classified as innovative and studies are ongoing to determine its performance in faecal sludge treatment. There are two type of solar drying technologies (covered and open drying), depending on how heat is supplied to the wet material and how moisture is evaporated (Kamil Salihoglu et al., 2007). For faecal sludge drying, the process is performed in drying beds (Stringel et al., 2019), where the initial TS content in the sludge influences drying performance, drying duration and bed design (covered or open beds) (Tayler, 2018; Kamil Salihoglu et al., 2007). For transparent assessment, this study compared covered drying beds with other treatment technologies.

3.2.2. Co-composting

This is the biological process of breaking down organic substrates (faecal sludge and solid biodegradable waste) in the presence of oxygen. The process generates heat, providing good conditions for pathogen deactivation if it can be maintained in the thermophilic range (40–70°C) (Tayler, 2018; Cofie et al., 2016). Co-composting of faecal sludge and organic solid waste is advantageous as the two waste materials complement each other, e.g. faecal sludge has a high nitrogen and moisture content, while organic solid waste has a high organic matter content, resulting in a suitable C:N ratio (25–35:1) for effective composting (Cofie et al., 2016; Enayetullah and Sinha, 2013). The preferred mixing ratio (by volume) of food market waste and dewatered faecal sludge is 2:1 (Cofie and Kone, 2009). Feedstock with initial dry solids content of 40–45% can enable effective composting (Tayler, 2018), but most food wastes have a considerably lower dry solids content. By recycling mature compost, it is possible to improve the compost structure and dry matter content, while producing a more stable end-product.

3.2.3. Vermicomposting

This non-thermophilic process uses earthworms together with microorganisms to convert organic waste into a humus-like product similar to compost (Cofie et al., 2016; Adi and Noor, 2009). Earthworms improve air circulation in the compost pile, maintaining aerobic conditions (Nigussie et al., 2016). The optimal moisture content for vermicomposting is 40–45%, while the temperature for optimal earthworm growth is 25–40 °C (Cofie et al., 2016). Earthworms are sensitive to the environment and usually move out of the culture boxes to suitable zones in waste when unfavourable conditions develop in terms of e.g. temperature, moisture, pH level, aeration or ammonia concentration (Dominguez, 2004). Material containing much easily available carbon produces an unfriendly environment for earthworms and needs to be pre-processed prior to being added to vermicomposting or added in very thin layers (Lalander et al., 2015). The process of worm collection and rearing (vermiculture) is an essential step for large-scale vermicomposting (Ntiamoah et al., 2014). Since the process is mesophilic, the end-product needs additional treatment for complete pathogen removal (Semiyaga et al., 2015).

3.2.4. Black soldier fly larvae (BSFL) composting

This non-thermophilic method uses fly larvae to convert organic matter (faecal sludge) into larval biomass and a compost (frass) in an aerobic batch process performed in thin layers (Lalander et al., 2019; Lalander et al., 2017). Feedstock with a dry solids content of 10–40% is most suitable for BSFL composting (Tayler, 2018) and the optimal temperature for larval growth is 29–31 °C (McConville et al., 2020b). Since the process is mesophilic, the end-product needs additional treatment for complete pathogen removal (McConville et al., 2020b).

3.3. Multi-criteria assessment (MCA) of secondary treatment technologies

The secondary treatment technologies described above were evaluated based on selected sustainability criteria (Table 4), using the respective indicators and sub-indicators listed in Table 1.

The scores obtained for the health criteria revealed that only co-composting met the standards for Class A biosolids for all pathogens under USEPA part 503 rules and WHO guidelines. End-products from the other treatment technologies would need additional

Table 4
Total score obtained for selected sustainability indicators (health, environmental, economic, socio-technical) and their respective sub-indicators in multi-criteria assessment (MCA) of four faecal sludge secondary treatment options for Phnom Penh, Cambodia. Where a five-point score (red=1, amber=2, yellow=3, light green=4, dark green=5) could not be applied to a sub-indicator, a three-point scale was used (1, 3, 5). Treatment technologies are (a) solar drying, (b) co-composting, (c) vermicomposting and (d) black soldier fly larvae composting.

Indicator	Sub-indicator	Treatment technology				Total score
		(a)	(b)	(c)	(d)	
Health criteria						30
Sanitisation efficiency of the treatment	Total coliforms/E-coli	3	5	1	3	12
	Faecal streptococci/ enterococcus	3	5	1	1	10
	Helminth eggs	1	5	1	1	8
Environmental criteria						46
Energy requirement	Potential energy demand by treatment system	3	3	5	3	14
Land requirement	Total land area required to operate the system	5	5	5	5	20
Climate impact	GHG emissions from the treatment system	3	1	3	5	12
Economic criteria						38
Investment cost	Total investment cost to build the system	3	3	3	1	10
Operation & maintenance (O&M)	Total O&M cost for daily operation	5	3	3	1	12
End-product value	Value of treatment end-product based on local classification	3	3	5	5	16
Socio-technical criteria						88
Robustness of technology	Level of technology development	3	5	3	3	14
	Capacity to endure shock load-quality of input material	4	3	2	3	12
	Capacity to endure shock load-quantity of input material	4	4	3	3	14
	Resilience against climate change impact-flooding	1	1	1	1	4
Public acceptance of treatment end-products	Public acceptance of treatment end-product to grow inedible plants, trees and grass	4	4	4	4	16
	Public acceptance of treatment end-product to grow food eaten by animals	3	4	4	3	14
	Public acceptance of treatment end-product to grow food for humans	4	4	3	3	14

post-treatment (chemical or thermal sanitisation, extended storage before use) for pathogen removal before using the product for food crop production.

For the environmental criteria, all four technologies obtained the same score for the space requirement sub-indicator and all required less space than the baseline option (planted drying bed). In terms of energy requirement, co-composting, solar drying, and BSFL composting all required some energy, e.g. for mechanical turning in co-composting and for ventilation in solar drying and BSFL composting. No energy was required for vermicomposting, resulting in a higher score (Table 4). The climate impact in terms of GHG emissions varied between the technologies, with co-composting having the highest potential emissions, followed by solar drying, vermicomposting and BSFL composting in that order.

BSFL composting received the lowest score for the economic criteria, since it had the highest investment and O&M costs. However, this technology gave added value in terms of the treatment end-products, i.e. larvae and the compost-like frass. Similarly, vermicomposting provided worms as the additional end-product to compost. However, the O&M costs were lower for vermicomposting than for BSFL composting, and more similar to those of co-composting. Solar drying had the lowest O&M costs, but also a lower volume of end-product (with similar value to compost).

The scores for the robustness of technology indicator showed best performance for co-composting, followed by solar drying, vermicomposting and BSFL composting in that order (Table 4).

Regarding public acceptance of treatment end-products, those from all four technologies had high public acceptance when used to grow inedible plants, with at least 70% acceptance reported by the respondents. There was some variation between the sub-indicators in public acceptance of treatment end-products for growing food eaten by animals and for growing food for humans. Solar drying and BSFL composting achieved only 58% and 55% acceptance, respectively, for use of the end-products to grow food eaten by animals. Co-composting achieved high acceptance for use of the end-products to grow food for humans (70%), while solar drying, vermicomposting and BSFL composting received lower scores (60%, 59% and 55%, respectively).

3.4. Stakeholder discussions and ranking

In addition to providing input on selection of locally relevant indicators, the sanitation sector stakeholders were engaged in weighing the five sustainability criteria for assessment of the four technologies. When opinions from both sector stakeholder groups (officials, NGOs and development partners) were averaged, the environmental criteria received the highest score (24.6%) and socio-technical criteria the lowest (16%) (Table 5). Individually, public officials gave most emphasis to the environment, followed by health and economic criteria, with socio-technical and institutional criteria given similar low weighting. In contrast, NGOs and development partners rated institutional criteria as the most important for identifying the treatment technology that best suits the Phnom Penh context, since they considered institutional structures to be key for failure/success in implementation of any project/programme.

The four technologies were then ranked based on their total score in MCA (Table 4) combined with their weighing score from sanitation sector stakeholders (Table 5). Since the institutional criteria were excluded from MCA, they were also excluded from this ranking step, so the weights do not add up to 100% for the different technologies. In the overall ranking (Table 6), co-composting had the highest normalised score, followed by solar drying (see Table S9 in SI for full details). Vermicomposting ranked third, while BSFL composting ranked lowest (Table 6). The ranking after normalisation did not change between the different sanitation sector sub-groups.

4. Discussion

In this study, MCA was performed to judge the appropriateness of the four shortlisted secondary treatment technologies for effective faecal sludge management in Phnom Penh. Co-composting ranked the highest, because it performed well in several sustainability aspects (pathogen elimination, robustness, public acceptance of treatment end-products). In particular, high scores for the health criteria were the reason why co-composting out-performed the other options. When managed correctly, co-composting can reach thermophilic temperatures (Tayler, 2018; Cofie et al., 2016), which can deactivate pathogens in the end-product, while the other technologies assessed operate under non-thermophilic conditions. Thus co-composting meets the USEPA Class A requirements for biosolids used in agriculture. However, if Class B requirements are applied and the end-product is not used in producing crops for human consumption (Tayler, 2018), then solar drying could be a good alternative since it is a simpler process than co-composting, especially if additional pathogen inactivation by biological treatment/stabilisation is included to decrease the risk of pathogen

Table 5
Scores given by sanitation sector stakeholders (n = 13) to different sustainability criteria (health, environmental, economic, socio-technical, institutional) in assessment of faecal sludge secondary treatment technologies (solar drying, co-composting, vermicomposting, and BSFL composting). DPs: development partners; NGOs: non-government organisations.

Sustainability criteria	Weighted score given by public sector officials (%)	Weighted score given by DPs/NGOs (%)	Average weighted score (%)
Health	21.0	19.4	*20.2*
Environment	31.0	18.1	*24.6*
Economic	20.6	19.4	*20.0*
Socio-technical	13.8	18.1	*16.0*
Institutional	13.6	25.0	*19.3*
Total	100.0	100.0	*100.0*

Table 6
Normalised total score and ranking of relevant sustainability criteria (health, environmental, economic, socio-technical) in assessment of faecal sludge secondary treatment technologies based on locally adapted sub-indicators specific to the Phnom Penh context.

Sustainability criteria	Average weight score (%) given by sector stakeholders	Normalised score			
		Solar drying	Co-composting	Vermi-composting	BSFL composting
Health	20.2	4.71	10.1	2.02	3.37
Environmental	24.6	5.88	4.81	6.95	6.95
Economic	20.0	5.79	4.74	5.79	3.68
Sociotechnical	16.0	4.18	4.55	3.64	3.64
Total	80.8	20.6	24.2	18.4	17.6
Final ranking		2	1	3	4

regrowth or re-contamination later in the process (Elving et al., 2010). An additional treatment step to ensure pathogen removal could also be introduced following BSFL composting or vermicomposting, e.g. the feedstock could be thermophilic composted for nine days followed by vermicomposting for 2.5 months (Nair et al., 2006) or the frass from BSFL could be thermally composted as it is still very biologically active material. These combined treatments would improve the outcome in terms of the health criteria, but would probably increase the investment and O&M costs.

If institutional criteria were included in the assessment (which was not possible in this study), solar drying might be the highest-ranking option and co-composting might score worse, since solar drying is not reliant on functional logistics to gain access to other feedstock while co-composting requires organic waste as feedstock. Solar drying is also less complicated to operate and can handle different types of incoming feedstock, such as faecal sludge and dewatered sludge (Tayler, 2018). It is questionable whether sanitation sector stakeholders in low-income countries could perform vermicomposting or BSFL composting, given the fact that these are sensitive processes and require skilled staff for daily operation and maintenance, unlike solar drying and co-composting (Tayler, 2018). Since sector stakeholders appear to lack knowledge on certain treatment options, vermicomposting and BSFL composting technologies would require significant investment in capacity development and training before being introduced (Rao et al., 2017). Therefore, it is less likely that these two options would be chosen in practice, although their end-products have higher value for reuse.

Vermicomposting and BSFL composting performed well with respect to environmental criteria, specifically climate impact, while co-composting performed worse owing to the high operating temperature needed to maintain thermophilic conditions during composting (Tayler, 2018; Cofie et al., 2016), which potentially resulted in higher methane and nitrous oxide emissions (Ermolaev et al., 2019; Ermolaev et al., 2014). There is thus a high likelihood of vermicomposting or BSFL composting being chosen if the decision is based solely on environmental impact.

Vermicomposting and BSFL composting also outperformed the other two options in terms of economic criteria and would be the probable choice if more weight is given to this aspect. Resource recovery from these two processes had higher reuse potential (Zabaleta et al., 2020; Lalander et al., 2017; Huis et al., 2013), which could potentially offset the treatment cost. However, it is unclear whether there is a market for larvae and worms locally in Phnom Penh. The respondents surveyed in this study indicated a few key challenges to take into account when promoting recycled products, such as trustworthiness of quality of final product, certificate on safe reuse and building trust among farmers to ensure there is a potential market for treatment end-products. The respondents recommended further studies on product quality to ensure safe reuse, since health is likely to be a key concern for both farmers and consumers when considering reuse opportunities. Previous scoping reviews on consumer acceptance of recycled products have found that perceived product quality is a key influencing factor in consumer acceptance and that the acceptance level is still unclear (Liu et al., 2022; Polyportis et al., 2022).

When implementing co-composting for faecal sludge treatment in Phnom Penh, primary treatment technologies that could produce dewatered sludge with a TS content of 20–40% would be necessary, while initial dry solids of 40–45% would enable good composting performance (Tayler, 2018). Coordination between key stakeholders would be needed to ensure good availability of organic waste feedstock for co-composting. This would require the city departments responsible for faecal sludge management and municipal solid waste management in Phnom Penh to cooperate in the early stages of planning for faecal sludge treatment (RGC, 2022). Composting plants for solid waste treatment implemented by NGOs have already been operating for many years, e.g. COMPED (Cambodia Education and Waste Management Organization) established a plant in 2000 (comped-cam.org). Therefore, stakeholder capacity for implementing co-composting exists in Phnom Penh. To ensure sustainable implementation of any new faecal sludge treatment technology, there is also a need to conduct market analyses to understand the potential market and commercial attractiveness of treatment end-products (Schoebitz et al., 2016).

5. Conclusions

This work provided site-specific and general insights into technology choices to be considered when planning for faecal sludge treatment. The shortlisted treatment technologies assessed were identified in a general context, meaning that the results are reproducible and can be used in the early planning of treatment in cities facing faecal sludge management challenges. A prerequisite screening step allowed elimination of non-feasible options and identification of options that were locally adapted to Phnom Penh and could be applied in similar cities, especially in neighbouring countries. In addition, the four-step structured approach employed allowed sanitation sector stakeholders to be consulted and their opinions to be incorporated in identification of relevant sustainability indicators and sub-indicators, and in weighting different secondary treatment technologies for sludge removed from household containment units in Phnom Penh.

The four secondary treatment technologies evaluated all had their strengths and weaknesses in terms of the different sustainability criteria used in the assessment (health, environmental, economic, socio-technical, institutional). Vermicomposting and BSFL composting provided good resource recovery and lower GHG emissions, but extra costs for additional post-treatment to ensure pathogen removal. Co-composting produced a safe, high-quality soil amendment, but required additional effort to set up logistical feedstock arrangements between stakeholders. Solar drying was a less complicated process, but could meet only Class B biosolids requirements.

Consideration of multiple sustainability criteria in assessment of potential technologies would allow planners and decision-makers to adopt a wider perspective on the available options and take trade-offs into account. The results obtained in this study can act as data support in the multiple-stakeholder discussions needed to take informed and appropriate decisions on future faecal sludge management in Phnom Penh.

CRediT authorship contribution statement

Chea Eliyan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jennifer McConville**: Conceptualization, Investigation, Validation, Methodology, Supervision, Writing – review & editing. **Christian Zurbrügg**: Methodology, Supervision, Writing – review & editing. **Thammarat Koottatep**: Methodology, Supervision, Writing – review & editing. **Kok Sothea**: Funding acquisition, Methodology, Supervision, Writing – review & editing. **Björn Vinnerås**: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request. All relevant data are included in the paper or attached as Supplementary Information.

Acknowledgements

The Swedish International Development Cooperation Agency fully supported this study through the "Sweden-Royal University of Phnom Penh Bilateral program" [Contribution Number: 11599]. Special thanks to Annika Nordin for her advice on the assessment of health criteria in MCA. The authors thank all stakeholders for their valuable time and inputs to data collection in this study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2023.103384.

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Sustainability assessment of faecal sludge treatment technologies for resource recovery in Phnom Penh, Cambodia

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Content of this supplementary material:

(1) Supplementary information I (SI): Structured questionnaire for interviewing with sanitation stakeholders

(2) Supplementary information II (SII): Survey questionnaire on public acceptance of faecal sludge treatment end products

(3) Table S1| Preliminary list of faecal sludge primary treatment technologies based on published literatures. FS: Faecal sludge, Dewater faecal sludge. Input material in this study are faecal sludge (black), dewater faecal sludge (brown) and the supernatant from the dewatering process (blue).

(4) Table S2| Preliminary list of faecal sludge secondary treatment technologies based on published literatures. Input material in this study are faecal sludge (black), dewater faecal sludge (brown) and the supernatant from the dewatering process (blue).

(5) Table S3| Details of scoring criteria to each sub-indicator under each dimension in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each technology.

(6) Table S4| Details of scoring criteria to health sub-indicators under health dimension in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology.

(7) Table S5| Details of scoring criteria for environmental sub-indicators in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5

considered the good performance of each secondary treatment technology. * means this assumption is based on expert judgment of authors.

(8) Table S6| Details of scoring criteria for economic sub-indicators in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology. * means this assumption is based on expert judgment of authors.

(9) Table S7| Details of scoring criteria for sociotechnical sub-indicators in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology. * means this assumption is based on expert judgment of authors.

(10) Table S8| Details of scoring criteria for sociotechnical sub-indicators in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology. * means this assumption is based on expert judgment of authors

(11) Table S9| Detailed normalized total score and ranking of sustainability assessment of faecal sludge secondary treatment technology based on locally adapted sub-indicator specific to Phnom Penh context. This assessment excluded the institutional criteria.

Supplementary Information (SI) I
Structured questionnaire for interviewing with sanitation stakeholders

General information and current mandate in relation to sanitation and faecal sludge management

- Mandate, vision, core mission of your organization in sanitation and faecal sludge management, including a new faecal sludge treatment plant[1].
- Legal and regulatory framework on sanitation and faecal sludge management.
- What are the criteria that you may use when selecting the treatment alternative for faecal sludge?
- What is the important category[2] in assessing the faecal sludge treatment systems? What should be the percentage for each category? (Note that total weigh is 100%)

Health and environment

- Is there standard quality of fertilizer for agricultural purpose (Pathogen level, nutrient content…) available?
- Is there wastewater effluent standard exist? Is there a separate effluent standard of wastewater and faecal sludge?
- Is there health standard for workers at treatment plant exist?

Finance

- Do you have any idea of how much does those treatment technology cost?
- How about their O & M cost?
- What criteria do recycled waste products need to meet to be appropriate for agricultural application and/or source of energy (eg. % of nitrogen and phosphorus content for fertilizer and calorific value for energy)?

Socio-technical

- Have you ever heard about reuse, recycle and recovery products from faecal sludge?
- What are the challenges in promoting recycled product (fertilizer and energy) from faecal sludge, in your view?

Institutional capacity

- Is your organization capable to offer the training for your staff or others stakeholders on resource recovery from faecal sludge? If not, do you think that it is possible to get this training from other organizations?
- How do you ensure that you have enough capacity to handle the FSM (for new treatment plant) within your mandate?
- Have your staff been regularly trained in technical duties (your mandate in sanitation service chain and for new treatment faecal sludge treatment plant)? If yes, how often the training is organized per year?

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[1] PPCA is in charge of coordinating all aspects of faeal sludge value chain, including reuse and valorization. Waste management and environment division is appointed to take the responsibilities in faecal sludge management value chain implementation. Other stakeholders included: DPWT, DLMUC, DoE and DAFF.

[2] Need to clearly define and explain the definition of each category after/before asking this question

- Do you have regular plan to provide capacity building to your staff to implement technical duties (your mandate in sanitation service chain and for new faecal sludge treatment plant)? If yes, how often is it updated? Do you feel that the plan is followed?
- Is there any protocol to carry out technical duties within your mandate available for new staff?
- Is there any regular funding available to implement sanitation improvement (or resource recovery) within your mandate?
- How good are you in attracting external funding from donors?
- Is there any existing funded project related to sanitation being implemented? If yes, what is the project about? Funding agency?
- Is there regular budget allocation for implementation new activities or capacity to look for funding exist in your institution?
- What is your role in new faecal sludge treatment plant (both in construction and operation phases)?
- Is there plan for operating new faecal sludge treatment plant (specifically your duties) or management structure exist?

Supplementary information II (SII)

Survey on public acceptance of faecal sludge treatment end products

This survey is part of the degree project within PhD education at the department of Energy and Technology, Swedish University of Agricultural Sciences, Sweden.

My name is Chea Eliyan, I am conducting a research on “Resource Recovery for Sustainable Sanitation Management in Phnom Penh, Cambodia”. The overall aim of the study is to identify the opportunities for resource recovery from faecal sludge from onsite sanitation and thus provide the inclusive sanitation service in Phnom Penh. This survey is part of my research project which aims to identify faecal sludge treatment technologies with potential resource recovery that are relevant and adoptable for a developing city like Phnom Penh to minimize the exposure to faecal sludge contaminants and indiscriminate disposals within neighborhoods and the environment. The revenue from recovering resources as the treatment end products could entirely or partially offset the operation and maintenance cost of the treatment systems which could be an attractive solution for sanitation stakeholders to implement an effective faecal sludge management in a city wide scale.

We, therefore, request for your personal opinion to the statements of four different technologies concerning fertilizer from faecal sludge. Those four technologies will be briefly described in their respective section. Note that we ask for your personal opinion, not any potential policy from your superior or such.

It could approximately take 15-20 minutes to fill up the form. The information you will be providing us will be confidential and only the researchers who are involved in this study will have access to it. Your data will also be stored without your name or any other kind of link that would enable us to identify what data is yours. Therefore, it will be available for use in future research studies forever and cannot be removed.

Section 1: Overview

Please mark only one answer that applies. Rate how well it matches your opinion.

1. Do you consent to take part in this study?

☐ Yes
☐ No

2. How old are you?

☐ 18-29
☐ 30-39
☐ 40-49
☐ 50-59
☐ 60+

3. Gender identity

☐ Male
☐ Female
☐ Prefer not to say

4. What is the highest level of education that you completed? * If you select "Other" please specify in the following.

☐ No formal education
☐ Incomplete primary school (grade 1-5)
☐ Primary school (grade 6)
☐ Lower secondary school (grade 9-11)
☐ Secondary school (grade 12)
☐ Beyond secondary school (diploma/technician))
☐ Bachelor degree
☐ Master degree or higher
☐ Other

5. Other from the previous question……………………………………………..

6. What institution do you work for?

☐ I am still a student
☐ Research/academia/education
☐ Government/public sector
☐ Private sector/company
☐ Non governmental/not for profit/civil society organization
☐ UN/International Development Organization
☐ Other

7. Other from the previous question……………………………………………..

8. To what sector do you belong? More than one answers is possible. * If you select "Other", please specify in the following.

☐ Agriculture, forestry and fishery
☐ Economic and finance
☐ Environment
☐ Engineering
☐ Marketing, services and sales
☐ Management
☐ Health
☐ Social science
☐ Technicians and associated professionals
☐ Other

9. Other from the previous question……………………………………………..

10. Environmental questions are important to me personally.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

11. Faecal sludge can be as safe fertilizer after treatment.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

12. Use of faecal sludge fertilizer will be harmful for the environment.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

13. Use of faecal sludge fertilizer will be harmful for my health.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

14. I think it is acceptable to use faecal sludge fertilizer to grow inedible plants such as follower and grass.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

15. I would be willing to eat animal meat that was fed by food grown with faecal sludge fertilizer

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

16. I would be willing to eat food grown with faecal sludge fertilizer

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

17. To randomize the order of the following questions, please choose the top alternative in the list (not part of the actual survey)

- ☐ ** (Go to section 2)
- ☐ ## (Go to section 2)
- ☐ ¤¤ (Go to section 2)
- ☐ %% (Go to section 2)
- ☐ && (Go to section 6)

Section 2: Faecal sludge treatment technology

This section will drive you through the four different faecal sludge treatment technologies. You will state your opinion to the statements about them concerning fertilizer from faecal sludge treated by different technology.

Rate how well the following statements match your opinions.

Solar drying technology

Solar drying: Uses greenhouse structure to dry sludge and it could be operated in either bath or continuous modes. It takes 10-20 days for processing. However, the number of days would depends on the weather condition. It takes shorter time during summer but longer in winter season. It is a low energy requirement and investment costs technology. The pathogens reduction level is reported varied from studies. Therefore the biosolids produces from this technology should be at best considered as class B biosolids, suitable to be applied for growing vegetables that are not eaten raw.

Rate how well the following statements match your opinions.

18. Use of faecal sludge fertilizer treated by solar drying will be harmful for the environment

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

19. Use of faecal sludge fertilizer treated by solar drying will be harmful for my health.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

20. I think it is acceptable to use faecal sludge fertilizer treated by solar drying to grow inedible plants such as flowers, trees, and grass.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

21. I would be willing to each animal meat that was fed by food grown with faeal sludge fertilizer treated by solar drying.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

22. I would be willing to eat food fertilized by faecal sludge treated by solar drying.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

Co-composting:

Co-composting: Dewatered sludge is mixed with organic waste as a ratio of 1:2 or 1:3. It takes 10-12 weeks with temperature between 50-70ºC. Thermophilic composting can have almost 100% pathogens reduction and low helminth eggs viability.

Rate how well the following statements match your opinions.

23. Use of faecal sludge fertilizer treated by co-composting will be harmful for the environment

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

24. Use of faecal sludge fertilizer treated by co-composting will be harmful for my health.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

25. I think it is acceptable to use faecal sludge fertilizer treated by co-composting to grow inedible plants such as flowers, trees, and grass.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

26. I would be willing to each animal meat that was fed by food grown with faeal sludge fertilizer treated by co-composting.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

27. I would be willing to eat food fertilized by faecal sludge treated by co-composting.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

Vermicomposting:

Vermicomposting: A low cost treatment technology using earthworms to composting faecal sludge. The optimum C/N is 30-35%. The number of fecal e.coli group in end products may still not meet the organic fertilizer standard, as it needs additional necessary measures to kill the fecal coliform such as high temperature drying treatment.

Rate how well the following statements match your opinions.

28. Use of faecal sludge fertilizer treated by vermicomposting will be harmful for the environment

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

29. Use of faecal sludge fertilizer treated by vermicomposting will be harmful for my health.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

30. I think it is acceptable to use faecal sludge fertilizer treated by vermicomposting to grow inedible plants such as flowers, trees, and grass.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

31. I would be willing to each animal meat that was fed by food grown with faeal sludge fertilizer treated by vermicomposting.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

32. I would be willing to eat food fertilized by faecal sludge treated by vermicomposting.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

BSFL (Black Soldier Fly Larvae) composting:

BSF composting: Aerobic treatment that use BSFL to decompose the organic matter contents in sludge. It could reach 6 log reduction in salmonella spp. in eight days. However, t is not an adequate sanitization method for agricultural reuse since there is no reduction of enterococcus and ascaris. It needs further treatment for agricultural reuse.

Rate how well the following statements match your opinions.

33. Use of faecal sludge fertilizer treated by BSFL composting will be harmful for the environment

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

34. Use of faecal sludge fertilizer treated by BSFL composting will be harmful for my health.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

35. I think it is acceptable to use faecal sludge fertilizer treated by BSFL composting to grow inedible plants such as flowers, trees, and grass.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

36. I would be willing to each animal meat that was fed by food grown with faeal sludge fertilizer treated by BSFL composting.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

37. I would be willing to eat food fertilized by faecal sludge treated by BSFL composting.

	1	2	3	4	5	
Do not agree at all	○	○	○	○	○	Completely agree

Section 3: Concluding

38. The following faecal sludge treatment technologies would produce safe fertilizer. You may need to scroll to see the all the 5 technologies and the rating scale. Rate how well it match your opinions. “1” Do not agree at all; “5” Completely agree.

	1 “Do not agree at all”	2	3	4	5 “Completely agree”
Solar drying	○	○	○	○	○
Co-composting	○	○	○	○	○
Vermicomposti...	○	○	○	○	○
BSF composting	○	○	○	○	○

39. Do you have any comments or questions to the survey or the study in general?

End of the survey!

Table S1| Preliminary list of faecal sludge primary treatment technologies based on published literatures. FS: Faecal sludge, Dewater faecal sludge. Input material in this study are faecal sludge (black), dewater faecal sludge (brown) and the supernatant from the dewatering process (blue).

Process group	**Treatment technology**	**Input material**	**Specification**	**References**
Physical	Drying bed	■	It consists of unplanted and planted drying bed. For unplanted bed, sand and gravel filter bed with and under-drain at the bottom. Wet sludge is discharged onto the beds at a depth of 200-300mm and left for percolation through the beds and evaporate from the surface until sufficiently dryness. Around 50-80% of liquid fraction can be removed which to collect and treat prior discharge. The remaining sludge needs to be treated before further application since it still contains high pathogens levels. It is easy to operate and low cost option but has odor potential. The planted bed, also called vertical flow constructed wetland, reed bed, planted dewatering bed or sludge bed with emergent plants. Plant in the drying bed help to improve the performance of the treatment system, thus treatment end-products are more stabilized and less presence of pathogens.	(Tayler, 2018; Singh *et al.*, 2017; Strande *et al.*, 2014)
Physical	Centrifugation	■	Faecal sludge places inside the centrifuge and rotate in a high speed, thus accelerate the sedimentation process. It is a mechanical dewatering system that is mostly applied for treatment of sludge residual in large-scale centralized wastewater treatment plants. The higher power consumption, higher maintenance costs and high noise levels are the limitation of this treatment system. It is not recommended for solid liquid separation of septage and faecal sludge.	((Tayler, 2018; Strande *et al.*, 2014)
Physical	Settling-thickening tank	■	A rectangular tank with the receiving sludge on one side and supernatant exiting on the other side. The solid fraction is settled at the bottom of the tank. Lime stabilization and ammonia treatment could be the next treatment options to achieve further reduction of pathogens, odor and organic matter.	(Tayler, 2018; Singh *et al.*, 2017; Strande *et al.*, 2014)
Physical	Imhoff tank	■	A two-storey tank that use gravity to separate liquid from solid fraction, called primary sedimentation. It requires low land and low cost for O &	

Process group	**Treatment technology**	**Input material**	**Specification**	**References**
			M. owever, It gives slow reduction of pathogens, thus further treatment is required before further application.	(Tayler, 2018; Singh *et al.*, 2017)
Physical	Geobags	⬛ ⬜ ⬜	Geobags or geotubes are flexible bags, fabricated from the high strength, permeable textiles. It works as filter to dewater of wet sludge as pressure inside the bag forces water out. Polymer dosing is necessary to achieve the satisfactory dewatering level while mixing is difficult and time consuming.	(Tayler, 2018; Singh *et al.*, 2017)
Chemical	Coagulation and flocculation	⬛ ⬜ 🟦	Coagulation and flocculation are achieved by adding of strong acid or base to destabilize particles, allowing them to come in contact with each other, form larger flocs and settle. Generally performed in a settling-thickening tank.	(Strande *et al.*, 2014)
Chemical	Conditioning	⬛ 🟫 🟦	The process is based on the same physical properties as coagulation and flocculation and can be carried out prior to the dewatering process to enhance the performance. Factors to consider for selecting chemicals such as pH, source, solid concentration, alkalinity. To implement this technology for faecal sludge, laboratory and pilot scale testing is necessary.	(Strande *et al.*, 2014)

Table S2| Preliminary list of faecal sludge secondary treatment technologies based on published literatures. Input material in this study are faecal sludge (black), dewater faecal sludge (brown) and the supernatant from the dewatering process (blue).

Process group	**Treatment technology**	**Input material**	**Specification (pros and cons)**	**End-product**	**References**
Physical	Pelletizing	⬜ 🟫 ⬜	Cost effect drying process, required 50-60% of FS dryness, reduce transport and storage cost. Treatment capacity could be 10,000m^2/400m^3/day. High ash content remains a challenge for pelletizing since it reduces the energy value of pellets. Ash could be melted during in high temperature and form clinker which could clog the gasifier.	Pellets	(Gold *et al.*, 2015) SEEK project
Thermo-chemical	Pyrolysis	⬜ 🟫 ⬜	Conversion of biomass in the absence of oxygen into solids, liquid and gases. Optimum holding time is 10min and temperature 350ºC produce suitable char characteristics for fuel and 450 or 600ºC for carbon sequestration. FS char had soil enhancement characteristics comparable to bio-waste and lignocellulosic biomass chars.	Biochar	(Krueger *et al.*, 2020; Gold *et al.*, 2018; Gold *et al.*, 2015)
Thermal	Hydrothermal carbonization	⬛ 🟫 ⬜	A waste to energy method which converts wet organic matter into carbonaceous solid called hydrochar in a short time (1-5hrs) at temperature range from 180-250ºC and pressure of 20-30 bar. It could be also applied for faecal sludge. Its advantage over other thermal conversion technologies is its ability to convert faecal sludge to hydrochar without dewatering and drying process, thus requires less energy input. However, pilot or full scale study is recommended to determine its and performance and economic feasibility.	Biochar	(Harder *et al.*, 2019; Fakkaew *et al.*, 2018) (Gold *et al.*, 2015) FaME project-Sandec
Physical	Drying bed (Solar drying)	⬛ 🟫	This technology could be in an open or covered greenhouse structure to dry sludge. This study referred to the covered drying bed. It could be operated in either bath or continuous modes with control condition in greenhouse. It takes 10-20 days for processing. However, the number of days would	Stabilized sludge	(Singh *et al.*, 2017)

Process group	**Treatment technology**	**Input material**	**Specification (pros and cons)**	**End-product**	**References**
			depends on the weather condition. It takes shorter time during summer but longer in winter season. It is a low energy requirement and investment costs technology.		
Biological	Co-composting	🟫	Dewatered sludge is mixed with organic waste as a ratio of 1:2 or 1:3. It takes 10-12 weeks with temperature between 50-70ºC. This technology gives high reduction of pathogen and helminth eggs but needs skillful staff to operate to achieve safe end -products.	Stabilized organic matter	(Singh *et al.*, 2017)
Biological	Deep row entrenchment	🟫	The trenches are filled in by sludge and covered by soil. Trees are planted on the top and absorb the organic matter and nutrients that are slowly released from faecal sludge. The limitation of this technology are high land requirement and unfeasible for areas with low groundwater table.	Fertilizer /Soil amendment	(Singh *et al.*, 2017)
Biological	Vermi-composting	🟫	A treatment technology that use earthworms to convert organic matter (faecal sludge) to humus like product, similar to compost. The optimum C/N is 30-35%. Since its operation is non-thermophilic condition, it is not a reliable method to ensure adequate pathogens removal. This technology is still under development and the worms can be quite susceptible to toxics materials and requires a longer operation time than co-composting.	Worms biomass and vermi-compost	(Singh *et al.*, 2017; Strande *et al.*, 2014)
Biological	Anaerobic digestion	🟫	This technology degrades the organic matter in faecal sludge with presence of anaerobic microorganisms (absence of oxygen). The amount of biogas generated depends on the organic matter content in faecal sludge. The key design parameters for this technology are hydraulic retention time (HRT), temperature and loading pattern.. It needs expert design and skilled labor for construction, operation and maintenance of anaerobic digester. This technology has also not proven for treating faecal sludge.	Biogas and slurry	(Tayler, 2018; Singh *et al.*, 2017; Tyagi & Lo, 2013)

Process group	**Treatment technology**	**Input material**	**Specification (pros and cons)**	**End-product**	**References**
Biological	Black soldier fly larvae (BSFL) composting	🟫	Aerobic treatment that use BSFL to decompose the organic matter contents in sludge. The larvae can be harvested as a protein feed for animals. The compost needs further treatment for pathogen removal.	Compost, protein (larvae)	(Singh *et al.*, 2017; Strande *et al.*, 2014)
Biological	Co-treatment in waste stabilization ponds	⬛ 🟦	This technology is considered good option for treating wastewater in low-income countries where adequate land is available. With addition of faecal sludge to waste stabilization ponds, ammonia quickly becomes a limiting factor to degrade organic matter content in faecal sludge. Ammonia is toxic to anaerobic bacteria. Aeration can be implemented to ensure adequate oxygen, which also helps to emit it as gaseous ammonia. Co-treatment may be applied with adequate precautions against overloading of organic matter.	Stabilized sludge	(Tayler, 2018; Strande *et al.*, 2014)
Chemical	Ammonia treatment	⬛ 🟫 🟦	An addition of ammonia to faecal sludge to inactivate microorganisms. Pathogen elimination will also depend on temperature and total ammoniacal nitrogen concentration.	Stabilized sludge	(Strande *et al.*, 2014)
Chemical	Alkaline stabilization	⬛ 🟫	Lime is used as alkaline material for wastewater sludge treatment to achieve the reduction of pathogens, degrade organic matter, reduce odours and improve sludge conditioning. It is applicable in either pre- or post-dewatered sludge. The main disadvantage of this technology are the requirement of lime and a dry storage area (as lime has a strong reaction with moisture and high risks of hazard to the eyes skin and respiratory system), and potential pathogens regrowth. It thus required skilled staff to follow health and safety procedures.	Stabilized sludge	(Tayler, 2018; Strande *et al.*, 2014)
Chemical	Oxidation		A polishing step to achieve final reduction of in pathogens and is not a primary form of FS treatment. Disinfection methods include chlorination, ozonation, and UV. However,	Disinfected effluent	(Strande *et al.*, 2014)

Process group	Treatment technology	Input material	Specification (pros and cons)	End-product	References
		🟦	chlorination is not effective for disinfecting faecal sludge or liquid effluent that contain high organics.		

Table S3: Details of scoring criteria to each sub-indicator under each dimension in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each technology.

Indicator	Sub-indicator	Scoring criteria	Score
Health criteria			
Sanitisation efficiency of the treatment	Total coliforms/E.coli	No reduction of total coliforms	1
		The reduction of total coliforms/E.coli meets Class B requirement for bio-solid by USEPA	3
		The reduction of total coliforms/E.coli meets Class A requirement for bio-solid by USEPA	5
	Fecal streptococci/ Enterococcus[3]	No reduction of enterococcus	1
		The reduction of enterococcus does not meet the national standard requirement of less than 5.10^3/g compost	3
		The reduction of enterococcus meets the national standard requirement of less than 5.10^3/g compost	5
	Helminth eggs	No reduction of helminth eggs	1
		The reduction of helminth eggs does not meet Class A requirement for bio-solid by USEPA	3
		The reduction of helminth eggs meets Class A requirement for bio-solid by USEPA	5
Environmental criteria			
Energy requirement	Potential energy demand by the treatment system[4]	The whole system needs energy	1
		There is electrical energy demand to operate some part of the system	3
		No energy needed to operate the whole system	5
Area requirement	Total land area requires to operate they system[5]	Lower solid loading rate (<200 Kg TS/m^2 year)	1
		Solid loading rate 200-250 Kg TS/m^2 year (reference to planted drying bed, the first faecal sludge treatment plant in Phnom Penh)	3
		Higher solid loading rate (>250 Kg TS/m^2 year)	5

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[3] Standard specification of group of organic fertilizer in Cambodia must have enterococcus less than 5.10^3/g compost (MAFF, 2012)

[4] The scoring to this sub-indicator was weighted against the planted drying bed for planned faecal sludge treatment plant. The system is under construction and expected to be ready for operation in 2023.

[5] The same as number 4.

Indicator	Sub-indicator	Scoring criteria	Score
Climate impact	GHGs emission by the treatment system[6]	GHGs emission of more than 2.1 kg/$CO_{2eq.}$ /ton of wet weigh of feedstock	1
		GHGs emission of 2.1 kg/$CO_{2eq.}$/ton of wet weigh of feedstock (GHG emission from sludge treatment reed bed was built with concrete)	3
		GHGs emission of less than 2.1 kg/$CO_{2eq.}$ /ton of wet weigh of feedstock	5
Economic criteria			
Investment cost	Total investment cost to build the system[7]	Investment cost is double as compared to planted drying bed	1
		Investment cost is the same planted drying bed	3
		Investment cost is 50% cheaper than planted drying bed	5
Operation and maintenance cost (O&M)	Total O&M cost for daily operate the system[8]	O & M cost is 50% higher than planted drying bed	1
		Approximately 25% higher than planted drying bed	3
		O & M cost is the same for the operation of planted drying bed, considering less skill staff requirement	5
End product value	Value of treatment end product based on local market[9]	The value of treatment end products is 50% less than product from planted drying bed	1
		The value of treatment end products is similar as product from planted drying bed	3
		The value of treatment end product(s) is higher than product from planted drying bed	5
Sociotechnical criteria			
Robustness of technology	Level of technology development	The treatment technology is at innovative stage	1
		The treatment technology is at transferring level	3
		The treatment technology is at established level	5
		If the entire system risked to be out of service or not having capacity to treat the incoming waste	1

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[6] The scoring to this sub-indicator employed the reference baseline GHGs emission from sludge treatment in reed bed in Hadsten, Denmark (Uggetti *et al.*, 2012)

[7] The same as number 4: exclusive of land cost, project management and other cost such as consultant…

[8] The same as number 4

[9] Humus potential price in Phnom Penh market is 5-15USD/bag 50kg based on field survey with 93 samples of households and with fertilizer retailers by GRET – we assumed that the quality of the end product will be similar and thus will have the same price/kg

Indicator	Sub-indicator	Scoring criteria	Score
	Capacity to endure shock load-quality of input material	If parts of the system risked to be out of service or not having capacity to treat the incoming waste	2
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity negatively	3
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity minimally	4
		If the system was not expected to be affected	5
	Quality to endure shock load-quantity of input material	If the entire system risked to be out of service or not having capacity to treat the incoming waste	1
		If parts of the system risked to be out of service or not having capacity to treat the incoming waste	2
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity negatively	3
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity minimally	4
		If the system was not expected to be affected	5
	Resilience against climate change impact-flooding	If the entire system risked to be out of service or not having capacity to treat the incoming waste	1
		If parts of the system risked to be out of service or not having capacity to treat the incoming waste	2
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity negatively	3
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity minimally	4
		If the system was not expected to be affected	5
Public acceptance of treatment end products	Public acceptance of treatment end product to grow inedible plants, trees and grass	Very low (< 20% of public acceptance)	1
		Low (≥ 20% and < 40% of public acceptance)	2
		Medium (≥ 40% and <60% of public acceptance)	3
		High (≥ 60% and <80% of public acceptance)	4
		Very high (≥ 80% of public acceptance)	5
		Very low (< 20% of public acceptance)	1

Indicator	Sub-indicator	Scoring criteria	Score
	Public acceptance of treatment end product to grow foods eaten by animals	Low (≥ 20% and < 40% of public acceptance)	2
		Medium (≥ 40% and <60% of public acceptance)	3
		High (≥ 60% and <80% of public acceptance)	4
		Very high (≥ 80% of public acceptance)	5
	Public acceptance of treatment end product to grow foods for humans	Very low (< 20% of public acceptance)	1
		Low (≥ 20% and < 40% of public acceptance)	2
		Medium (≥ 40% and <60% of public acceptance)	3
		High (≥ 60% and <80% of public acceptance)	4
		Very high (≥ 80% of public acceptance)	5

Table S4: Details of scoring criteria to health sub-indicators under health dimension in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology.

<table>
<tr><th colspan="4">Scoring criteria</th></tr>
<tr><td>Indicator</td><td>Sub-indicator</td><td>Scoring criteria</td><td>Score</td></tr>
<tr><td rowspan="9">Sanitisation efficiency of the treatment</td><td rowspan="3">Total coliforms/E.coli</td><td>No reduction of total coliforms</td><td>1</td></tr>
<tr><td>The reduction of total coliforms/E.coli meets Class B requirement for bio-solid by USEPA</td><td>3</td></tr>
<tr><td>The reduction of total coliforms/E.coli meets Class A requirement for bio-solid by USEPA</td><td>5</td></tr>
<tr><td rowspan="3">Fecal streptococci/ Enterococcus</td><td>No reduction of enterococcus</td><td>1</td></tr>
<tr><td>The reduction of enterococcus does not meet the national standard requirement of less than 5.10^3/g compost</td><td>3</td></tr>
<tr><td>The reduction of enterococcus meets the national standard requirement of less than 5.10^3/g compost</td><td>5</td></tr>
<tr><td rowspan="3">Helminth eggs</td><td>No reduction of helminth eggs</td><td>1</td></tr>
<tr><td>The reduction of helminth eggs does not meets Class A requirement for bio-solid by USEPA</td><td>3</td></tr>
<tr><td>The reduction of helminth eggs meets Class A requirement for bio-solid by USEPA</td><td>5</td></tr>
<tr><th colspan="4">Details information used to make scoring to each treatment technology</th></tr>
<tr><td>Treatment technology</td><td>Total coliform/E.coli</td><td>Fecal streptococci/enterococcus</td><td>Helminth eggs</td></tr>
<tr><td rowspan="2">Solar drying</td><td>3</td><td>3</td><td>1</td></tr>
<tr><td colspan="3">Assuming that pathogenic load range for faecal sludge are 2,500-60,000 helminth eggs/L and 10^5-10^6 faecal coliforms/100ml (Afolabi & Sohail, 2017). Time requires to achieve up to 95% dry solid content ranged between 8 and 31 days. However, it does not ensure the complete sanitization of sewerage sludge. Pathogen reduction in solar drying varies between studies: some considered it only meeting Class B biosolids standards (Tayler, 2018), while others report 96% removal of pathogens during summer and 60% during winter (An-nori <i>et al.</i>, 2022). Log reductions of only three orders of magnitude for total coliform reduction and two orders of magnitude for Enterococcus could be achieved, so further sludge processing such as lime or thermal treatment is needed for pathogen removal to meet class A requirements (An-nori <i>et al.</i>, 2022; Mathioudakis <i>et al.</i>, 2013; Mathioudakis <i>et al.</i>, 2009). Only 0.5 log reduction for helminth eggs (WHO, 2006)</td></tr>
<tr><td rowspan="3">Co-composting</td><td>Total coliform/E.coli</td><td>Fecal streptococci/Enterococcus</td><td>Helminth eggs</td></tr>
<tr><td>5</td><td>5</td><td>5</td></tr>
<tr><td colspan="3">Inactivating pathogens in compost is achieved by the heat generated in the process. It inactivates many pathogens and possibly kills helminth eggs (Zewde <i>et al.</i>, 2021). Thermophilic composting results in pathogen die-off , low helminth egg viability with at least two months of optimum composting (Strande <i>et al.</i>, 2014; WHO, 2006). To reach class A requirement, the windrow composting must be maintained at 55ºC for at least 15 days and turned at least 5 times (Tayler, 2018), while 1.5-2.0 log reduction of Helminth eggs could be achieved for the duration of three months (WHO, 2006).</td></tr>
</table>

Vermicomposting	Total coliform/E.coli	Fecal streptococci/Enterococcus	Helminth eggs
	🟥 1	🟥 1	🟥 1
	Vermicomposting cannot be operated at thermophilic conditions as in co-composting, thus it is limited in pathogens inactivation (Strande *et al.*, 2014). The number of fecal e.coli present after vermicomposting may still not meet the organic fertilizer standards and it may be necessary to take measures to kill the fecal coliform before reuse, such as high temperature drying treatment (Wang *et al.*, 2020). Required further treatment before reuse (McConville *et al.*, 2020b; Tayler, 2018).		
BSFL composting	Total coliform/E.coli	Fecal streptococci/Enterococcus	Helminth eggs
	🟨 3	🟥 1	🟥 1
	Achieved 6 log reduction in salmonella spp in eight days. (Lalander *et al.*, 2013). No reduction for ascaris suum ova. BSFL cannot considered as adequate sanitization method for fecal matter to remove ascaris for agricultural reuse. No reduction for enterococcus (Lalander *et al.*, 2013). Required further treatment before reuse (McConville *et al.*, 2020b; Tayler, 2018).		

Table S5: Details of scoring criteria for environmental sub-indicators in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology. * means this assumption is based on expert judgment of authors.

Scoring criteria for environmental criteria			
Indicator	Sub-indicator	Scoring criteria	Score
Energy requirement	Potential energy demand by the treatment system	The whole system need energy	1
		There is electrical energy demand to operate some part of the system	3
		No energy needed to operate the whole system	5
Area requirement	Total land area requires to operate the system	Lower solid loading rate (<200 Kg TS/m^2 year)	1
		Solid loading rate 200-250 Kg TS/m^2 year (reference to planted drying bed, the first faecal sludge treatment plant in Phnom Penh)	3
		Higher solid loading rate (>250 Kg TS/m^2 year)	5
Climate impact	GHGs emission by the treatment system	GHGs emission of more than 2.1 kg $CO_{2eq.}$/ton of wet weigh of feedstock	1
		GHGs emission of 2.1 kg $CO_{2eq.}$/ton of wet weigh of feedstock (GHG emission from sludge treatment reed bed was built with concrete)	3
		GHGs emission of less than 2.1 kg $CO_{2eq.}$/ton of wet weigh of feedstock	5

Details information used to make scoring to each treatment technology			
Treatment Technology	Energy requirement	Area requirement	Climate impact
Solar drying	Energy requires for mechanical turning and ventilation-20-60kWh/ton, (Stringel *et al.*, 2019; Tayler, 2018)	500 kg TS/m^2/year (Tayler, 2018)	This process emits very low GHG emission (Stringel *et al.*, 2019). Indoor temperature in covered drying bed was 11±2ºC higher than outdoor temperature (Kamil Salihoglu *et al.*, 2007), then temperature in drying is lower than composting since methane emission is correlated with temperature (Ermolaev *et al.*, 2014)
	3	5	3
Co-composting	30-55 kWh/ton for mechanical turning of windrow composting (Zabaleta *et al.*, 2020)	180-300 m^2/ton/day (Zabaleta *et al.*, 2020) Or 608-365 kg TS/m^2/year Processing time (3-6 months)	Total emission from windrow composting (CH_4 and N_2O) was 19.2KgCO_2eq./ton food waste treated (Ermolaev *et al.*, 2019; Ermolaev *et al.*, 2012)
	3	5	1
Vermicomposting	There is no energy needed, except for other operation such as lighting etc. (Zabaleta *et al.*, 2020)	300-580 m^2/ton/day (Zabaleta *et al.*, 2020) Or 365-189 kg TS/m^2/year Processing time (1.5-2.5 months)	Less GHG emission as compared to thermal composting (Nigussie *et al.*, 2016), thus could potentially emit similar emission to solar drying*
	5	5	3
BSFL composting	90-105 kWh/ton for ventilation to supply oxygen to the BSFL production. (Zabaleta *et al.*, 2020; Tayler, 2018)	500-750 m^2/ton TS/day (Tayler, 2018) Or 1,217-629 kg TS/m^2/year Processing time (14 days) (Zabaleta *et al.*, 2020)	BSFL treatment emits less GHGs compared to conventional composting method (0.38KgCO_2eq/ton food waste treated) (Chen *et al.*, 2019; Ermolaev *et al.*, 2019) (Lindberg *et al.*, 2022)
	3	5	5

Table S6: Details of scoring criteria for economic sub-indicators in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology. * means this assumption is based on expert judgment of authors.

Scoring criteria for economic criteria			
Indicator	Sub-indicator	Scoring criteria	Score
Investment cost	Total investment cost to build the system	Investment cost is double as compared to planted drying bed	1
		Investment cost is the same planted drying bed	3
		Investment cost is 50% cheaper than planted drying bed	5
Operation and maintenance cost (O&M)	Total O&M cost to daily operate the system	O & M cost is 50% higher then planted drying bed	1
		Approximately 25% higher then planted drying bed	3
		O & M cost is the same for the operation of planted drying bed, considering less skill staff requirement	5
End product value	Value of treatment end product based on local market	The value of treatment end products is 50% less than product from planted drying bed	1
		The value of treatment end product is similar as product from planted drying bed	3
		The value of treatment end product(s) is higher than product from planted drying bed	5

Details information used to make scoring to each treatment technology			
Treatment technology	Investment cost	O & M cost	End product value
Solar drying	Additional investment for greenhouse roof-Low investment*	Considerable low operating cost (Stringel *et al.*, 2019), this could probably as low as planted drying bed.	Solids produced is considered as Class B biosolids and has similar value as product from co-composting, could be used to grow vegetable that is not for eaten raw (Tayler, 2018)
	3	5	3
Co-composting	Additional investment for mechanical turning. Low investment*	Additional power and skilled labor needed to ensure the proper operation (regular turning). O&M cost could then be higher (25%) than planted drying bed*	130$/ton of compost (Enayetullah & Sinha, 2013) Compost quality depends on feedstock and quality control during operation (Zabaleta *et al.*, 2020)
	3	3	3
Vermicomposting	Additional investment for compartment for worms-low investment*	Need skilled labor to operate and growth the worms. O&M cost could then be higher (25%) than planted drying bed *	200$/ton (compost and worms) (Huis *et al.*, 2013) Vermicompost has higher nutrient than compost (Zabaleta *et al.*, 2020) and worms
	3	3	5
BSFL composting	Additional investment for specialized compartment for larvae-double investment cost*	Requires regular monitoring of BSF reproduction and growth to ensure reliable supply as well as power for ventilation. Considerable 50% higher O &M cost compared to planted drying bed.*	Total value of 125.6€/ton feedstock (compost value: 23.6 and larval biomass 102€) (Lalander *et al.*, 2017) 200$/ton (compost and larval biomass (Huis *et al.*, 2013). Residue from the process also contain nutrient and further treatment required to avoid oxygen depletion (Zabaleta *et al.*, 2020)
	1	1	5

Table S7: Details of scoring criteria for sociotechnical sub-indicators in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology. * means this assumption is based on expert judgment of authors

Scoring criteria for sociotechnical criteria			
Indicator	Sub-indicator	Scoring criteria	Score
Robustness of technology	Level of technology development	The treatment technology is at innovative stage	1
		The treatment technology is at transferring level	3
		The treatment technology is at established level	5
	Capacity to endure shock load-quality of input material	If the entire system risked to be out of service or not having capacity to treat the incoming waste	1
		If parts of the system risked to be out of service or not having capacity to treat the incoming waste	2
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity negatively	3
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity minimally	4
		If the system was not expected to be affected	5
	Quality to endure shock load-quantity of input material	If the entire system risked to be out of service or not having capacity to treat the incoming waste	1
		If parts of the system risked to be out of service or not having capacity to treat the incoming waste	2
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity negatively	3
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity minimally	4
		If the system was not expected to be affected	5
	Resilience against climate change impact-flooding	If the entire system risked to be out of service or not having capacity to treat the incoming waste	1
		If parts of the system risked to be out of service or not having capacity to treat the incoming waste	2
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity negatively	3
		If the system was expected to continue operating but with temporary operating errors, affecting the treatment capacity minimally	4
		If the system was not expected to be affected	5

Details information used to make scoring to each treatment technology				
Treatment technology	Level of technology development	Capacity to endure shock load-quality of input material	Capacity to endure shock load-quantity of input material	Resilience against climate change impact-flooding
Solar drying	It has been used in large scale only to treat wastewater sludge. Pilot scale are being carried out but no information on the use of this	Influential factors to solar drying are solar radiation, air temperature, relative humidity, and sludge depth. (Tayler, 2018). Initial total solid	Sludge depth as one of the influential factors to the performance of the drying beds. The design of the beds therefore	Flooding may negatively affect the entire system since the system is supposed to have dry condition*.

	technology in low-middle income countries (Tayler, 2018; Strande *et al.*, 2014). It gains an interest to solve sewage sludge disposal (Stringel *et al.*, 2019)	content of the sludge could also influence the performance (duration of drying) (Tayler, 2018). Sludge quality is one of the factors which may extend the drying duration, slightly impacts the system*	based on the volumetric loading (Tayler, 2018). More sludge loading would extend the drying duration*	
	3	4	4	1
Co-composting	It is an established technology (Strande *et al.*, 2014)	Need to maintained moisture and C:N ratio correctly for optimum composting, (Tayler, 2018; Cofie *et al.*, 2016). Thus, quality shock load would cause temporary error to the system*.	If there is space at the treatment site, a new windrow could be started. So as long as there is space, the quantity loading could be adjusted. However, there might not be enough material (organic waste) to get the right balance.*	It is recommended that areas prone to flooding should be avoided (Tayler, 2018)
	5	3	4	1
Vermicomposting	It is in development for use with faecal sludge. Vermicomposting otherwise is a technology that has been used in household toilets in India and Ghana for quite sometime (Hylton *et al.*, 2022; Furlong *et al.*, 2014).	Need to maintain moisture content of (40-45%) Earthworms may die (susceptible in toxic condition) in the unfavorable condition (anaerobic, higher moisture…) (McConville *et al.*, 2020a; Cofie *et al.*, 2016; Strande *et al.*, 2014). Quality shock load would cause worms die off*.	The treatment system has been designed with the specific loading of feedstock and earthworms population (2-2.5 kg worms/m^2 (Zabaleta *et al.*, 2020) but new batch of worms could always start to handle extra incoming sludge*.	The entire system is sensitive to the environment, flooding may cause risk to the entire system*.
	3	2	3	1
BSFL composting	It is in development for use with faecal sludge. There are several large scale uses of BSF for food waste in low/middle income countries, but not as much with faecal sludge. Up scaling optimization and commercialization of this technology is recommended (Liu *et al.*, 2022)	Total solid for feedstock should be within range 20-30% and free of hazardous materials (Tayler, 2018). However, it is non-influential for variation in C:N ratio (Zabaleta *et al.*, 2020). Quality shock load would minimally affect the system*.	The BSF larvae do not strive to deeper than 225mm of waste (Tayler, 2018). It is risk that BSF could not consume the incoming feedstock at the bottom layer but extra batch process could easily start with incoming sludge*	BSF reproduction are sensitive to temperature and humidity. Optimum humidity for BSF reproduction is 70% (Tayler, 2018).
	3	3	3	1

Table S8: Details of scoring criteria for sociotechnical sub-indicators in multi-criteria assessment in step 3. Scoring scale is 1 to 5, 1 considered the worse performance and 5 considered the good performance of each secondary treatment technology. * means this assumption is based on expert judgment of authors

Scoring criteria for sociotechnical criteria			
Indicator	Sub-indicator	Scoring criteria	Score
Public acceptance of treatment end products	Public acceptance of treatment end product to grow inedible plants, trees and grass	Very low (< 20% of public acceptance)	1
		Low (≥ 20% and < 40% of public acceptance)	2
		Medium (≥ 40% and <60% of public acceptance)	3
		High (≥ 60% and <80% of public acceptance)	4
		Very high (≥ 80% of public acceptance)	5
	Public acceptance of treatment end product to grow foods eaten by animals	Very low (< 20% of public acceptance)	1
		Low (≥ 20% and < 40% of public acceptance)	2
		Medium (≥ 40% and <60% of public acceptance)	3
		High (≥ 60% and <80% of public acceptance)	4
		Very high (≥ 80% of public acceptance)	5
	Public acceptance of treatment end product to grow foods for humans	Very low (< 20% of public acceptance)	1
		Low (≥ 20% and < 40% of public acceptance)	2
		Medium (≥ 40% and <60% of public acceptance)	3
		High (≥ 60% and <80% of public acceptance)	4
		Very high (≥ 80% of public acceptance)	5

Details information used to make scoring to each treatment technology			
Treatment technology	Grow inedible plants, trees and grass	Grow foods eaten by animals	Grow foods for humans
Solar drying	70% of respondents thought it is acceptable to use treatment end product from solar drying to grow inedible plants, trees and grass	58% of respondents thought it is acceptable to eat animal meat that was fed by food grown with treatment end product from solar drying	60% of respondents would be willing to eat food fertilized by treatment end product from solar drying
	4	3	4
Co-composting	73% of respondents thought it is acceptable to use treatment end product from co-composting to grow inedible plants, trees and grass	67% of respondents thought it is acceptable to eat animal meat that was fed by food grown with treatment end product from co-composting	70% of respondents would be willing to eat food fertilized by treatment end product from co-composting
	4	4	4
Vermicomposting	72% of respondents thought it is acceptable to use treatment end product from vermicomposting to grow inedible plants, trees and grass	61% of respondents thought it is acceptable to eat animal meat that was fed by food grown with treatment end product from vermicomposting	59% of respondents would be willing to eat food fertilized by treatment end product from vermicomposting
	4	4	3

BSFL composting	71% of respondents thought it is acceptable to use treatment end product from BSLF composting to grow inedible plants, trees and grass	55% of respondents thought it is acceptable to eat animal meat that was fed by food grown with treatment end product from BSLF composting	55% of respondents would be willing to eat food fertilized by treatment end product from BSLF composting
	4	3	3

Table S9| Detailed normalized total score and ranking of sustainability assessment of faecal sludge secondary treatment technology based on locally adapted sub-indicator specific to Phnom Penh context. This assessment excluded the institutional criteria.

Indicator	Sub-indicator	Average Weight score by stakeholder (%)	Normalized score			
			(a)	(b)	(c)	(d)
Health dimension						
Sanitisation efficiency in treatment end product	Total coliforms/E.coli	20.2	2.02	3.37	0.67	2.02
	Fecal streptococci/ enterococcus		2.02	3.37	0.67	0.67
	Helminth eggs		0.67	3.37	0.67	0.67
Environmental dimension						
Energy requirement	Potential energy demand by treatment system	24.6	1.60	1.60	2.67	1.60
Land requirement	Total land area require to operate the system		2.67	2.67	2.67	2.67
Climate impact	GHGs emission by the treatment system		1.60	0.53	1.60	2.67
Economic dimension						
Investment cost	-	20	1.58	1.58	1.58	0.53
Operation and maintenance (O & M)	-		2.63	1.58	1.58	0.53
End product value	Value of treatment end product based on local classification		1.58	1.58	2.63	2.63
Sociotechnical dimension						
Robustness of technology	Level of technology development	16	0.55	0.91	0.55	0.55
	Capacity to endure shock load-quality of input material		0.73	0.55	0.36	0.55
	Capacity to endure shock load-quantity of input material		0.73	0.73	0.55	0.55
	Resilience against climate change impact-flooding		0.18	0.18	0.18	0.18
Public acceptance of treatment end products	Public acceptance of treatment end product to grow inedible plants, trees and grass		0.73	0.73	0.73	0.73
	Public acceptance of treatment end product to grow food eaten by animals		0.55	0.73	0.73	0.55
	Public acceptance of treatment end product to grow food for humans		0.73	0.73	0.55	0.55
Total			20.6	24.2	18.4	17.6
Final ranking			2	1	3	4

Note: (a) Solar drying, (b) Co-composting, (c) Vermicomposting, (d) Black soldier fly larvae composting.

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DOCTORAL THESIS NO. 2023:99

Proper faecal sludge management in low and middle-income countries is a great challenge. To support faecal sludge management planning at city scale, this thesis investigated resource recovery potential from faecal sludge. Three alternatives to tackle the challenges in faecal sludge management include; i) use of biosolids as soil conditioner; ii) upstream source control; and iii) source separation. These findings can assist sector stakeholders in Phnom Penh and other cities with comparable sanitation systems in improving faecal sludge management.

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ISSN 1652-6880
ISBN (print version) 978-91-8046-250-1
ISBN (electronic version) 978-91-8046-251-8