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

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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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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)

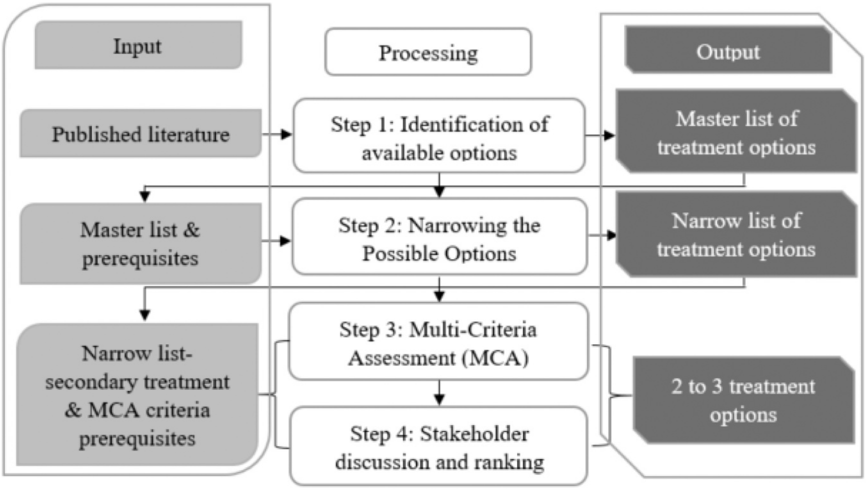

Fig. 1. Flow chart of the four-step structured approach applied in this study for ranking sustainable faecal sludge treatment technologies. The output from steps 1 and 2 was used as input to the next step. Steps 3 and 4 were performed in parallel and the same inputs were used for both.

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 subgroups.

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.

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Appendix A. Supporting information

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References

Adi, A.J., Noor, Z.M., 2009. Waste recycling: utilization of coffee grounds and kitchen waste in vermicomposting. Bioresour. Technol. 100 (2), 1027–1030.

Andersson, K., Rosemarin, A., Lamizana, B., Kvarnström, E., McConville, J., Seidu, R., Dickin, S. & Trimmer, C. (2016). Sanitation, Wastewater Management and Sustainability: from Waste Disposal to Resource Recovery. *Nairobi and Stockholm: United Nations Environment Programme and Stockholm Environment Institute.*

Andriessen, N., Strande, L., Ward, B.J., 2019. To char or not to char? Review of technologies to produce solid fuels for resource recovery from faecal sludge. J. Water, Sanit. Hyg. Dev. 9 (2), 210–224.

Benavides, L., Avellán, T., Caucci, S., Hahn, A., Kirschke, S., Müller, A., 2019. Assessing sustainability of wastewater management systems in a multi-scalar, transdisciplinary manner in latin America. Water 11 (2).

Cofie, O. & Kone, D. (2009). *Case study of SuSanA projects: Co-composting of faecal sludge and organic solid waste, Khumasi, Ghana.* Sustainable Sanitation Alliance. Available at ⟨http://www.susana.org/en/⟩.

Cofie, O., Nikiema, J., Impraim, R., Adamtey, N., Paul, J., Koné, D., 2016. Co-compoting of solid waste and fecal sludge for nutrient and organic matter recovery. Resource Recovery & Reuse Series 3: CGIAR Research Program on Water, Land and Ecosystems. International Water Management Institute (IWMI).

Diener, S., Semiyaga, S., Niwagaba, C.B., Muspratt, A.M., Gning, J.B., Mbéguéré, M., Ennin, J.E., Zurbrugg, C., Strande, L., 2014. A value proposition: Resource recovery from faecal sludge-can it be the driver for improved sanitation? Resour., Conserv. Recycl. 88, 32–38.

Dominguez, J., 2004. State-of-the-Art and New Perspectives on Vermicomposting Research. Earthworm Ecology, second ed. CRC Press LLC, Spain, pp. 401–421 (ed. Deparamento de Ecoloxia et Bioloxia Animal, Universidade de Vigo).

Doyle, S.E., 2013. City of Water: Architecture, Infrastrcuture and the Floods of Phnom Penh: Iowa State University. In: Drechsel, P., Qadir, M., Wichelns, D. (Eds.), Wastewater: Economic Asset in an Urbanizing World. Springer, Dordrecht Heidelberg New York London, 2015.

Drechsel, P., Qadir, M., Wichelns, D., 2015. Wastewater: Economic Asset in an Urbanizing World. Springer, Dordrecht Heidelberg New York London.

Eliyan, C., McConville, J.R., Zurbrügg, C., Koottatep, T., Sothea, K., Vinnerås, B., 2022a. Generation and management of faecal sludge quantities and potential for resource recovery in Phnom Penh, Cambodia. Front. Environ. Sci. 10.

Eliyan, C., Vinnerås, B., Zurbrügg, C., Koottatep, T., Sothea, K., McConville, J., 2022b. Factors influencing physicochemical characteristics of faecal sludge in Phnom Penh, Cambodia. J. Water, Sanit. Hyg. Dev.

Elving, J., Ottoson, J.R., Vinneras, B., Albihn, A., 2010. Growth potential of faecal bacteria in simulated psychrophilic/mesophilic zones during composting of organic waste. J. Appl. Microbiol 108 (6), 1974–1981.

Enayetullah, I. & Sinha, A.H.M.M. (2013). *Co-Composting of Municipal Solid Waste and Faecal Sludge for Agriculture in Kushtia Municipality, Bangladesh* .

Ermolaev, E., Lalander, C., Vinneras, B., 2019. Greenhouse gas emissions from small-scale fly larvae composting with Hermetia illucens. Waste Manag 96, 65–74.

Ermolaev, E., Sundberg, C., Pell, M., Jonsson, H., 2014. Greenhouse gas emissions from home composting in practice. Bioresour. Technol. 151, 174–182.

Frenoux, C., Tsitsikalis, A., 2015. Domestic private faecal sludge emptying services in Cambodia: between market efficiency and regulation needs for sustainable management. J. Water Sanit. Hyg. Dev. 05 (1), 13.

Frenoux, C., Tsitsikalis, A., Corre, M.L. & Carlier, R. (2011). *Landscap Analysis and Bussiness Model Assessment in Faecal Sludge Management: Extraction and Transportation Model-Cambodia*1-Main Report): GRET/Cambodia.

Gold, M., Niwagaba, C., Studer, F., Getkate, W., Babu, M., Strande, L., 2015. Production of pellets and electricity from faecal sludge. (Excreta Wastewater Manag. Sandec N. 16.

Gold, M., Cunningham, M., Bleuler, M., Arnheiter, R., Schönborn, A., Niwagaba, C., Strande, L., 2018. Operating parameters for three resource recovery options from slow-pyrolysis of faecal sludge. J. Water, Sanit. Hyg. Dev. 8 (4), 707–717.

Harder, R., Wielemaker, R., Larsen, T.A., Zeeman, G., Öberg, G., 2019. Recycling nutrients contained in human excreta to agriculture: pathways, processes, and products. Crit. Rev. Environ. Sci. Technol. 49 (8), 695–743.

Huis, Av, Itterbeeck, J.V., Klunder, H., Mertens, E., Halloran, A., Muir, G., Vantomme, P., 2013. Edible Insects Future Prospects for Food and Feed Security. Food and Agriculture Organization of the United Nations, Rome, Italy.

Irvine, K., Sovann, C., Suthipong, S., Kok, S. & Chea, E. (2015). Application of PCSWMM to Assess Wastewater Treatment and Urban Flooding Scenarios in Phnom Penh, Cambodia: A Tool to Support Eco-City Planning. *Journal of Water Management Modeling.*

JICA (2016). *The Study on Drainage and Sewerage Improvement Project in Phnom Penh Metropolitan Area.* Phnom Penh, Cambodia.

Jönsson, H., Stinzing, A.R., Vinnerås, B. & Salmon, E. (2004). *Guidline on the Use of Urine and Faeces in Crop Production.* (EcoSanRes Publications Series: the EcoSanRes Programme and the Stockholm Environment Institute.

Kamil Salihoglu, N., Pinarli, V., Salihoglu, G., 2007. Solar drying in sludge management in Turkey. Renew. Energy 32 (10), 1661–1675.

Katukiza, A.Y., Ronteltap, M., Oleja, A., Niwagaba, C.B., Kansiime, F., Lens, P.N., 2010. Selection of sustainable sanitation technologies for urban slums–a case of Bwaise III in Kampala, Uganda. Sci. Total Environ. 409 (1), 52–62.

Krueger, B.C., Fowler, G.D., Templeton, M.R., Moya, B., 2020. Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste. Water Res. 169, 115253.

Lalander, C., Nordberg, Å. & Vinnerås, B. (2017). A comparison in product-value potential in four treatment strategies for food waste and faeces – assessing composting, fly larvae composting and anaerobic digestion. *Global Change Biology: Bioenergy*.

Lalander, C., Diener, S., Zurbrügg, C., Vinnerås, B., 2019. Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (Hermetia illucens). J. Clean. Prod. 208, 211–219.

Lalander, C.H., Komakech, A.J., Vinneras, B., 2015. Vermicomposting as manure management strategy for urban small-holder animal farms - Kampala case study. Waste Manag. 39, 96–103.

Liu, T., Klammsteiner, T., Dregulo, A.M., Kumar, V., Zhou, Y., Zhang, Z., Awasthi, M.K., 2022. Black soldier fly larvae for organic manure recycling and its potential for a circular bioeconomy: a review. Sci. Total Environ. 833, 155122.

MAFF, 2012. Prakas on Procedures and Standard Requirements for Fertilizer Registrations. Royal Government of Cambodia, Minitry of Agriculture, Forestry and Fisheries, Phnom Penh, Cambodia.

McConville, J., Kvarnström, E., Nordin, A., Jönsson, H., Niwagaba, C., 2020a. Structured approach for comparison of treatment options for nutrient-recovery from fecal sludge. Front. Environ. Sci. 8, 36.

McConville, J., Niwagaba, C., Nordin, A., Ahlström, M., Namboozo, V. & Kiffe, M. (2020b). Guide to Sanitation Resource Recovery Products & Technologies: A supplement to the Compendium of Sanitation Systems and Technologies.

Nair, J., Sekiozoic, V., Anda, M., 2006. Effect of pre-composting on vermicomposting of kitchen waste. Bioresour. Technol. 97 (16), 2091–2095.

Nigussie, A., Kuyper, T.W., Bruun, S., de Neergaard, A., 2016. Vermicomposting as a technology for reducing nitrogen losses and greenhouse gas emissions from small-scale composting. J. Clean. Prod. 139, 429–439.

Nikiema, J., Cofie, O. & Impraim, R. (2014). *Technological options for safe resource recovery from fecal sludge.* (Resource Recovery & Reuse 2. Sri Lanka: CGIAR Research Program on Water, Land and Ecosystems, International Water Management Institute (IWMI).

NIS (2020). General Population Census of the Kingdom of Cambodia 2019: National Report on Final Census Results.

Ntiamoah, K.B., Adjei-Afful, E. & Kantanka, A.S. (2014). *The use of vermicomposting from organic food waste as a potential treat for topsoil in restoring biodiversity at quarry site reclamation at Beposo*. Ghana.

Peal, A., Evans, B., Blackett, I., Hawkins, P. & Heymans, C. (2015). *A Review of Fecal Sludge Management in 12 Cities* World Bank, Water and Sanitation Program.

Polyportis, A., Mugge, R., Magnier, L., 2022. Consumer acceptance of products made from recycled materials: a scoping review. Resour., Conserv. Recycl. 186.

PPCA (2021). *2035 Fecal Sludge Management Strategy for Phnom Penh Capital Administration* SIA Ingénieurie conseil and Phnom Penh Capital Adminstration.

Rao, K.C., Otoo, M., Drechsel, P., Hanjra, M.A., 2017. Resource recovery and reuse as an incentive for a more viable sanitation service chain. Water Altern. 10 (2), 493–512. *10(2): 493-512*.

RGC, 2022. Sub-Degree on The establishment of Enterprise for Managing Municiple Solid Waste in Phnom Penh. Phnom Penh, Cambodia.

Schoebitz, L., Andriessen, N., Bollier, S., Bassan, M., Strande, L., 2016. Market Driven Approach for Selection of Faecal Sludge Treatment Products. Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.

Semiyaga, S., Okure, M.A.E., Niwagaba, C.B., Katukiza, A.Y., Kansiime, F., 2015. Decentralized options for faecal sludge management in urban slum areas of Sub-Saharan Africa: a review of technologies, practices and end-uses. Resour., Conserv. Recycl. 104, 109–119.

Singh, S., Mohana, R.R., Rathi, S., Raju, N.J., 2017. Technology options for faecal sludge management in developing countries: benefits and revenue from reuse. Environ. Technol. Innov. 7, 203–218.

Spuhler, D., Scheidegger, A., Maurer, M., 2018. Generation of sanitation system options for urban planning considering novel technologies. Water Res. 145, 259–278.

Strande, L., 2014. The global situation. In: Strande, L., Brdjanovic, D. (Eds.), Faecal Sludge Management: Systems Approach for Implementation and Operation. IWA Publishing, London.

Strande, L., Ronteltap, M., Brdjanovic, D., 2014. Faecal Sludge Management: Systems Approach for Implementation and Operation. IWA Publishing.

Stringel, S.S., Mugauri, T., Singh, A. & Inambao, F. (2019). *Drying of Faecal Sludge using Solar Thermal Energy*: Water Research Commission.

SuSanA (2008). Towards more sustainable sanitation solutions (Version 1.2).

Tayler, K., 2018. Faecal Sludge and Septage Treatment: A Guide for Low and Middle Income Countries; Practical Action. Publishing Ltd., Rugby, UK.

Uggetti, E., Ferrer, I., Arias, C., Brix, H., García, J., 2012. Carbon footprint of sludge treatment reed beds. Ecol. Eng. 44, 298–302.

USEPA (1994). *A Plain English Guide to the EPA Part 503 Biosolids Rule*. Washington, DC: U.S. Environmental Protection Agency.

WHO (2006). *WHO guidelines for the safe use of wastewater, excreta and greywater*. France.

WHO & UNICEF (2017). *Progress on Drinking Water, Sanitation and Hygiene: 2017 update and SDG baselines*. Geneva.

WHO & UNICEF (2021). *Progress on household drinking water, sanitation and hygiene 2000–2020: five years into the SDGs*. Geneva:: World Health Organization (WHO) and the United Nations Children's Fund (UNICEF). Licence: CC BY-NC-SA 3.0 IGO.

Zabaleta, I., Mertenat, A., Scholten, L. & Zurbrügg, C. (2020). *Selecting Organic Waste Treatment Technologies. SOWATT* Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland.

Zewde, A.A., Li, Z., Xiaoqin, Z., 2021. Improved and promising fecal sludge sanitizing methods: treatment of fecal sludge using resource recovery technologies. J. Water Sanit. Hyg. Dev. 11 (3), 335–349.