Household Perceptions, Practices, and Experiences with Real-world Alternating Dual-Pit Latrines Treated with Storage and Lime in Rural Cambodia

Short Title: Household Practices with Alternating Dual-Pit Latrines in Rural Cambodia

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Abstract

Safely managed sanitation (SMS) has been difficult to achieve in resource-limited rural areas. To support achieving sustained SMS in rural Cambodia, iDE introduced the alternating dual-pit latrine (ADP), which treats fecal sludge (FS) on-site using storage and lime while maintaining latrine functionality. However, households must perform recommended practices, particularly regarding how and when they switch between pits, to achieve on-site FS treatment and safe disposal. We surveyed 770 rural households with fecal sludge management (FSM) experience to evaluate at scale how they operate and maintain their ADPs across five of 25 Cambodian provinces. Response frequencies, descriptive statistics, and regressions with five novel indices that describe households' practices and attitudes related to ADPs were calculated. Nearly two thirds of households (60%) did not know how long storage treatment must proceed until emptying can be performed safely, and no household waited the recommended two years to empty their pits. While households appreciated their ADPs' advantages (e.g., reduced costs and land requirements), only 14% followed recommended practices and switched their pits after emptying their disconnected pit. Most household practices varied by province, flood proneness, education, and other factors. To support achieving sustained rural SMS, various evidence-based sector recommendations are made.

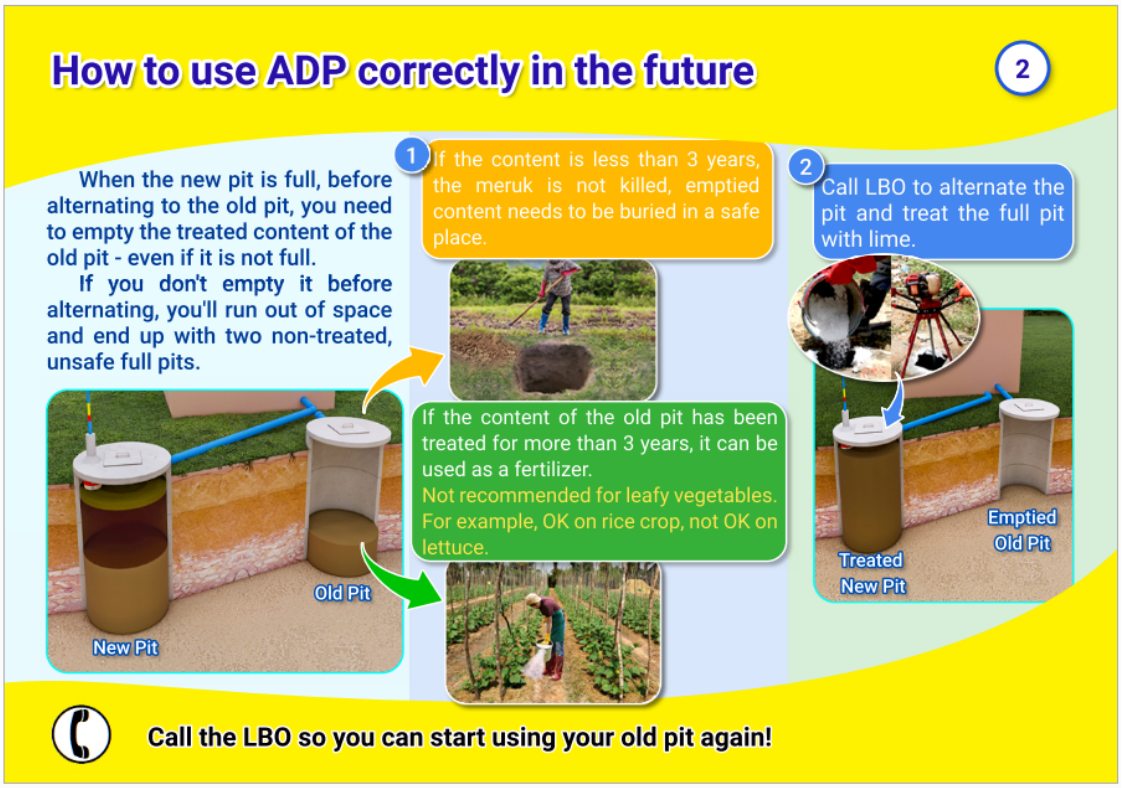
Keywords

fecal sludge management; on-site sanitation; behavior; public health; safely managed sanitation; toilet

Highlights

1. Household practices, perceptions, and experiences with real-world alternating dual-pit latrines were described.
2. Recommended practices were never followed by households that emptied their pits; no household waited two years to empty their old pit.
3. Knowledge about ADPs was poor: 60% of households did not know how long fecal sludge must undergo storage treatment before emptying can be performed safely.
4. Households appreciate the advantages of ADPs, including reduced costs and land requirements.

Graphical Abstract



1. Introduction

Safely managed sanitation (SMS) prevents exposure to enteric pathogens[1–3] by promoting safe and effective fecal sludge management (FSM), which describes how human feces and urine are contained, transported, treated, and disposed of or reused in situ or offsite.[4] A household's FSM system should also not be shared with other households according to the Joint Monitoring Program (JMP).

Rural sanitation development focuses on safely managed on-site sanitation (SMOSS) systems in many regions because of their reduced costs and complexities that do not require transporting fecal sludge (FS) over long distances for treatment and disposal.[5,6] SMOSS systems can provide treatment where FS is contained, allowing households to manage their own FS with reduced risk of exposure to pathogens.[5] Examples of SMOSS systems include alternating twin-pit latrines and composting toilets; however, SMOSS systems can also include single-pit latrines whose pits are simply capped when full and a new pit constructed.[7]

In recent years, across rural Cambodia, there has been a rapid expansion of basic sanitation coverage (i.e., improved sanitation systems that are used by only one household and hygienically separate human excreta from human contact[1]). Most rural households in Cambodia own a pour-flush pit latrine and empty their own pits using high-risk methods, posing a critical challenge of achieving rural SMS.[8] Today, rural sanitation in Cambodia is characterized by few pit-emptying service providers that are available and affordable, and little to no FSM infrastructure or enforced regulations that require FS to be treated, disposed of, and/or reused safely.[9] Based on sectoral experience in Cambodia and around the world, SMOSS are the current preferred solution in rural areas (i.e., on-site FS treatment followed by reuse of FS as fertilizer).[10]

Since 2009, iDE, a non-profit organization, scaled up an inclusive and sustainable sanitation-marketing program in rural Cambodia, which aims to create aspirational and effective sanitation products; manages sales agents to site and sell sanitation products; and trains and facilitates latrine business owners (LBOs) to install and service rural households' toilets. To support achieving sustained SMS in rural Cambodia, iDE introduced a new FSM product in 2017 - the alternating dual-pit latrine upgrade (ADP) with lime treatment.

The ADP was inspired by the traditional Alternating Twin-Pit design with context-appropriate modifications including an upgrade installation process to existing latrines, lime treatment, and a pit gauge that signals when a household's pit is nearly full.[10–12] iDE's ADP is sold and constructed as an upgrade to an existing single-pit latrine, where an additional ("new") pit is added to an existing single-pit latrine. The new pit allows FS to be treated on-site while maintaining latrine functionality and effectively doubles the households' hygienic FS storage capacity. Costing approximately $50 USD, an ADP upgrade is 16% less expensive than building a new single-pit latrine but maintains latrine functionality.[13] In addition to a reduced cost, rural Cambodian households prefer the reduced space required by ADPs compared to multiple single-pit latrines.[13]

ADP orders generated by iDE sales agents are assigned to local LBOs for product delivery and installation at the household location. Each LBO is trained by iDE to safely disconnect a household's connected pit from their toilet and treat the FS in the pit by mixing 6 kg of hydrated

lime. The LBO then installs and connects a new pit to the original latrine, enabling households to continue using their toilet. iDE and LBOs work together to ensure that ADPs are installed up to standards that meet site selection and lime treatment protocols (Figure S1 and ADP installation manual and technical guidelines in the Supporting Information).

When purchasing an ADP, iDE sales agents provide the household with a leaflet (Figure S2) that contains post-installation messages and steps to ensure proper SMS including emptying, treatment and disposal/reuse of FS while maintaining minimal exposure to pathogens. After two years of undergoing lime and storage treatment, as recommended by the WHO,[14] the original lime-treated pit can be emptied by the household using commonly available manual tools (e.g., shovels) without specific methods or equipment.[10] The emptied treated FS can then be reused in the form of fertilizer. When the pit connected to the pour-flush latrine in an ADP system is nearly full, iDE recommends the household to contact the LBO for a "pit switching" service. This pit switching service includes disconnecting the nearly full pit from the latrine, treating it by mixing lime, and connecting the household-emptied pit to the latrine to maintain toilet functionality. Following these steps in the recommended order is critical for households to achieve on-site treatment and safe disposal of FS with an ADP. Therefore, how rural Cambodian households operate and maintain their ADPs is of critical importance to achieve sustained SMS and is explored in detail in this study.

With over 22,000 rural Cambodian households using ADPs since 2017, this study can accurately evaluate the effectiveness of SMOSS systems like the ADP and progress towards sustained rural SMS through the FSM knowledge, perceptions, practices and experiences of households. This study investigates the research question "In rural Cambodia, do households appropriately operate and maintain their ADPs based on recommended practices?". The microbiology, specifically the reduction of important enteric pathogens in FS in real-world ADPs, is also examined in the companion study of this study and is reported in another article in tandem with this article.[15] That study, which is described in a companion article, provides relevant context to this study's results and should be considered together with this study for a more holistic description of household ADPs in rural Cambodia.

2. Methods

This study seeks to understand household approaches to using and maintaining their ADPs. Specifically, this study seeks to understand if households are operating and maintaining their ADP systems as recommended; what contextual factors might influence the use of ADP products; and what improvements could be made to ADPs to make them safer, more contextually appropriate, and more valuable to rural households.

Study Design, Sampling Frame, Inclusion Criteria, and Sample Size

To maximize the generalizability of the study's behavioral results to the larger rural Cambodian context, a novel behavioral sample was drawn from iDE's historical sales data of ADPs in five provinces across rural Cambodia where the ADP product is sold by local businesses at scale. A phone survey was then performed with selected households to identify households with filled pits using a simple random sample of iDE ADP owners. The main consideration driving the

sample criteria was ensuring that surveyed households would likely have experience with FSM and ADPs.

To understand how households manage their ADPs, households were only eligible for inclusion in the study if they owned their ADP latrine for more than two years and had switched their pit connections from one full pit to the other at least once since their ADP was installed. Contacted households were then given a brief eligibility criteria questionnaire, and all households included in the study met the inclusion criteria listed in the Supporting Information. After random sampling and eligibility was confirmed via phone call or field visits, the final total sample of households who performed the behavioral survey was 770. This study was approved by Solutions IRB on February 16, 2022 as an amendment to protocol number 2021/10/2.[16]

iDE's sales database contains 8,410 ADP products that were delivered two to three years prior to March 1, 2022. This total includes 300 pre-identified households with a full pit using an iDE's a random sample call center in 2021. Assuming homogeneous distribution of pit fill across provinces, there is approximately a 2,105 total population size of eligible ADPs. The research team used the population-known equation developed by Krejcie and Morgan (1970) to calculate required sample sizes based on the desired degree of precision (6%). Under these assumptions, the research team determined the minimum required sample size to be 765; more details are shown in Table S1.

Data Collection

A survey of approximately 40 minutes in duration was administered to 770 rural households in five of 25 Cambodian provinces where ADP installations were scaled. The complete survey used in this study is shown in the Supporting Information, and the following modules were included based on a review of previous literature and iDE's experiences and scale-up operations in rural provinces:

- ***Demographics***, including household size, highest education level of any household member, primary occupation or livelihood activities of household members, poverty status (IDPoor), gender of respondent, household members with disabilities, and ethnicity. Household poverty levels were self-reported using the Cambodian National Government's Identification of Poor Households (IDPoor) Programme metrics.[17]
- ***Latrine history and use information***, including number of pits, frequency of use, number of people using the latrine, sharing status, improvements, system modification (e.g., pierced pits) and maintenance issues (e.g., repairs).
- ***Knowledge of ADPs and FSM***, including understanding of FS dangers; pit-emptying and treatment processes that can improve safety; equipment and clothing used to empty pits safely; and methods of emptying pits.
- ***ADP History and Maintenance***, including how, when, and why households switched to ADP latrines, and ADP-specific maintenance issues (e.g., repairs).
- ***ADP FSM Experience***, including how, when, and why latrine was switched to a different pit; perceptions of expense, disgust, difficulty and safety; disposal location; method of disposal; and maintenance issues (e.g., repairs).
- ***Attitudes about ADP and FSM***, including, perceptions of ADPs, including safety, ease of use, maintenance, disgust, and affordability.

All interviews were conducted in-person using secure smartphones, and data was managed and stored on secure servers. Prior to beginning each interview, respondents were asked to provide verbal consent to participation after being informed of the purpose of the research, measures taken to protect their privacy, and their right to decline participation in the interview at any time. In cases where respondents did not consent to the survey, enumerators were instructed to record the reason why and immediately end the interview. All data are freely available at https://osf.io/uwq82/.

Data Analysis

Data were analyzed and grouped from the above modules to describe three primary topics related to household ADP behaviors: 1) knowledge and perceptions of ADPs and FSM; 2) practices and experiences with ADPs; and 3) common characteristics of households that use ADPs as recommended. Response frequencies characterized these aspects of households, and descriptive statistics were disaggregated by province and geographic area (flood-prone versus non-flood-prone), where relevant. To identify common characteristics among households that use ADPs as recommended by iDE after product installation (Figure S2), five novel indices were developed to describe households' practices and attitudes related to general best practices for ADPs, pit emptying, pit switching, FS treatment, and knowledge of and attitudes towards sanitation. These six Safe-FSM-Practices Probability Indices are described as follows:

1. The **Emptying Practices Index** describes how appropriately and safely households emptied their pit as recommended. Specific dimensions captured by this index include: whether the household ever emptied their pit; whether the pit was emptied by an appropriate service provider; whether the pit was emptied using appropriate methods and if the pit was pierced; whether the pit was left disconnected for a sufficient period of time before being emptied; and whether FS was disposed of in an appropriate location and using appropriate methods.
2. The **Switching Practices Index** describes whether households safely switched their latrine from one pit to another as recommended. Specific dimensions captured by this index include whether the old pit was emptied after the household changed their connection to the new pit; whether the old pit was emptied by an appropriate service provider; whether the old pit was left disconnected for a sufficient period of time (at least two years) before reconnection/reuse; whether the connection was changed by an appropriate service provider; and whether the old pit was disconnected from the toilet after switching pits.
3. The **Treatment Practices Index** describes how and when households treated FS stored in their pits in relation to recommended practices. Specific dimensions captured by this index include whether the household treated the new pit with lime before switching pits; whether lime treatment was performed by a trained service provider; and whether any product was used to treat waste in the pit before or after emptying.
4. The **Sanitation Knowledge Index** describes households' understanding of safe FS management practices. Specific dimensions captured by this index include whether the household understands that FSM affects the health of the household, that disposing of waste in a body of water is unsafe; and that disposing of waste in a field is unsafe.
5. The **Sanitation Attitudes Index** describes households' perceptions surrounding the importance of safe FS management practices. Specific dimensions captured by this index

include whether the household feels that killing pathogens in FS is important, that safety is a priority when disposing of waste from the pit, and that it is appropriate for a household member to empty the pit.

The survey questions used to create each index are shown in Table 1, and possible responses, scores, and score rationales are shown in Table S2. The responses to each question were scored on a three-point numeric scale that categorized the related practice, knowledge, or attitude as "contrary to recommended FSM practices" (0), "neither contrary to nor following recommended FSM practices" (1), and "following recommended FSM practices" (2). For questions with binary response options, responses were scored as "contrary to recommended FSM practices" (0) or "following recommended FSM practices" (2). The final score for each index was simply the average score for each response, which also standardized the indices. Possible scores on each index ranged from 0 to 2.

Table 1. Safe-FSM-Practices probability indices with questions that were used to construct them

Index	Question
Emptying Practices	Did the household empty their old pit?
	Who emptied the old pit?
	What methods were used to empty the old pit?
	Did the household pierce their pit?
	How many months was the old pit left disconnected from the toilet before it was emptied?
	Where was the FS disposed of?
	How was the waste disposed of?
Pit Switching Practices	When switched pits, was the old pit emptied when the new pit filled?
	When switched pits, who emptied the old pit?
	When switched pits, how many months was the old pit left disconnected from the toilet before it was emptied?
	Who switched the pits?
	When switched pits, was the old pit disconnected from the toilet until the new pit filled?
Treatment Practices	When switched pits, was the pit most recently connected to the toilet treated with lime?
	When switched pits, who performed the lime treatment in the pit most recently connected to the toilet?
	Was any product used to treat the FS in the pit most recently connected to the toilet?
Sanitation Knowledge	Know that FSM affects health
	Know that disposing FS into a body of water is unsafe
	Know that disposing FS onto a field is unsafe
	Know that the water that comes out of a pit above ground is unsafe
Sanitation Attitudes	Feels that killing pathogens in FS is important
	Feels that safety is a top consideration when considering where to dispose of FS
	Feels that a household member emptying a pit is unsafe

Each index was used as a dependent variable in different regression models that were designed to explore the relationship between household characteristics and these key dimensions of ADP operation and FSM. Household characteristics of interest included geographic location, climate vulnerability, education, poverty status, education, and pit overflow frequency (the number of times that FS exits a pit untreated). The explanatory variables used in this regression were selected because the literature reported that they likely affect one or multiple behavioral determinants of the FSM decision-making process.[9]

3. Results

The results of this study are divided into three key subsections: household knowledge and perceptions of ADPs and FSM; household practices and experiences with ADPs; and common

characteristics of households that use ADPs as recommended. Household demographics and socio-economic information are shown in the Supporting Information.

Household Knowledge and Perceptions of ADPs and FSM

Household knowledge of ADPs and FSM was generally poor, with few households understanding how an ADP should be operated to achieve SMS, specifically regarding storage treatment and the recommended time period to leave a pit untouched. Nearly two thirds of households (60%) did not know how long storage treatment must proceed until emptying can be performed safely, and 7% thought that less than one year of storage treatment was sufficient (Figure S4). Despite efforts to train households on the required duration of storage treatment, only 9% of households correctly believed that it was safe to empty their pits after 2-3 years of storage treatment.

Household perceptions about ADPs and FSM showed that households appreciate the advantages provided by an ADP compared to a single-pit latrine. In comparison to a single-pit latrine, households' perceived advantages of having an ADP included reduced costs and land requirements overtime (23%); doubled FS storage capacity (16%); improving the cleanliness of their environment and community (13%); and allowing continuous latrine use (10%; Figure S5). Most households (82%) also believe manual emptying to be unsafe, and nearly all households (97%) feel that FS treatment and safe disposal locations are important aspects of FSM (Figure S6); having access to safely managed sanitation/working toilet is important; and agree that safely emptying pits matches their family's and community's values and maintains good relationships with neighbors.

Household Practices Compared to Recommended Practices

Pit Switching

Pit-switching practices were found to vary widely and typically did not follow recommended practices. Among households that had experienced a full connected pit since their ADP had been installed, three-quarters (72%) either emptied their connected pit immediately themselves (31%), hired a service provider (24%), or pierced it to keep it from filling (15%). Only one quarter (28%) switched their pits; however, half of these households (51%) switched back to their disconnected pit *without emptying it* due to its increased available capacity via dewatering since it was disconnected, exposing the FS undergoing treatment to untreated FS and negating the treatment progress to date. Thus, only 14% of households switched their pit after emptying their disconnected pit.

Among households who switched their pits, nearly all (97%) switched their pits when their connected pit was full or nearly full (see "Household Practices Compared to Recommended Practices" in the Supporting Information). A quarter of households reported they switched their connection because their latrine would no longer flush, which typically indicates a full pit. Only 9% of households switched their pit because their Pit Gauge indicated that it was time to switch.

Pit switching also varied by province and flood proneness (Table S3). Only 10% of households switched their pits in Svay Rieng province, while 36% switched in Siem Reap. Households in

flood-prone areas reported switching their connection more frequently than those in other regions (63% vs. 37%, respectively); this topic is described in detail in another article that is currently in preparation.[18]

Treatment

Household treatment practices similarly did not follow recommended practices. Treating a filled pit with lime after switching pits was uncommon across surveyed households (16%; n = 219). A lack of required materials, primarily lime, (33%) and a lack of available service providers (23%) were the most common reasons for not treating with lime. Among households who did treat their full pit with lime, half (54%) reported that lime treatment was performed by a trained professional, and 40% had treated their pit themselves.

Recommended practices were surprisingly never followed by households that emptied their pits. Among households that emptied their pits, no household waited two years to empty their old pit, and more than half (59%) waited less than 1 year (see "Household Practices Compared to Recommended Practices" in the Supporting Information). Only 9% of households reported waiting longer than a year and a half.

Common Characteristics of Households that Use ADPs as Recommended

The five Safe-FSM-Practices Probability Indices were found to vary by many factors, including province, flood proneness, poverty, education, and the number of pit-overflow events. The following results describe some common characteristics of households that do and do not use ADPs as recommended.

The use of recommended emptying practices was described by the Emptying Practices Index and varied by province, education, and the frequency of pit-overflow events but not flood proneness or poverty (Table S4). Households in Prey Veng and Svay Rieng followed recommended emptying practices less frequently than those in other provinces (β = -0.20 and -0.40, respectively), while those in Siem Reap followed recommended emptying practices more (β = 0.13). Having formal primary and secondary education was surprisingly associated with performing recommended emptying practices less frequently (β = -0.20 and -0.15, respectively). This result disagrees with the literature, which reports that more education, particularly attaining at least a primary education, is associated with performing safe FSM practices.[19] Lastly, having experienced more pit-overflow events, which was more common at flood-prone households, was increasingly associated with performing recommended emptying practices less frequently (β = -0.58 to -0.66).

Switching pits using recommended practices was described by the Switching Practices Index and varied by poverty and education but not province, flood proneness, or the frequency of pit-overflow events (Table S5). Having IDPoor 1 status was associated with a marked decrease in safe pit-switching practices (β = -0.45). Having vocational education was associated with a slight decrease in safe pit-switching practices (β = -0.15) and may be due to an increased confidence to perform skilled labor (e.g., switch a pit) produced by such education.[20]

Treating FS using recommended practices was described by the Treatment Practices Index and varied by flood proneness, poverty, and the frequency of pit-overflow events but not province or education (Table S6). Households living in flood-prone regions typically performed FS treatment less frequently than those living in non-flood-prone regions (β = -0.19). This result is consistent with the literature, which states that flood proneness increases challenges related to latrine functionality and can increase unsafe FSM practices to solve these challenges.[18] Treatment practices generally improved as pit-overflowing events increased in frequency (β = 0.34 to 0.57), implying that increased exposure to FS may impart a desire to treat the pathogens it contains to reduce health risks; however, this conjecture should be investigated in future research. Lastly, IDPoor 1 status was associated with a marked increase in safe treatment practices (β = 1.27).

Households' sanitation knowledge was described by the Sanitation Knowledge Index and varied by province, poverty, education, and the frequency of pit-overflowing events but not flood proneness (Table S7), as in other studies.[11] Households in Siem Reap knew the most about sanitation (β = 0.12), while those in Kandal knew the least (β = -0.11). Households with a member that had completed only primary or vocational school knew less than other households (β = -0.21 and -0.42), and IDPoor 1 status was associated with increased sanitation knowledge compared to other households (β = 0.24). Lastly, more frequent pit-overflow events were associated with less sanitation knowledge, implying that households that knew less about the dangers of unsafe FSM practices are more comfortable with allowing their pit to overflow and the associated health risks.

Sanitation attitudes were described by the Sanitation Attitudes Index and varied by province and flood proneness but not poverty, education, or the number of pit-overflow events (Table S8). Households in Prey Veng and Svay Rieng were the least concerned with safe FSM (β = -0.19 and -0.14, respectively), and those in Kandal and Siem Reap were slightly more concerned (β = -0.09), while households in Kampong Thom were most concerned (β = 0.00). Flood proneness was also associated with less concern for safe FSM (β = -0.09), highlighting yet another challenge in flood-prone regions: unsafe perceptions to FS in water as increased exposure to FS may impart a desire to safely manage sanitation, this should be investigated in future research.

4. Discussion/Conclusion

Most households did not follow the recommended ADP operational practices, and all households that emptied their pit did not wait the WHO-recommended two years, risking direct exposure to untreated waste. Although a lack of sanitation knowledge may be a contributor to this result, this study shows that when a pit filled, most households choose either to empty their connected pit immediately (31%) or pierce their pit to prevent it from overflowing (34%; Supporting Information). These unsafe practices have been linked in other studies to a desire for convenience and to reduce costs by avoiding service provider costs.[12] In this study, unsafe practices are also linked to a lack of access to affordable, convenient FSM services (i.e. safe emptying and disposal) beyond ADP installation and lime treatment. Households also typically waited until their pit was full or nearly full before considering switching their connection, putting them at risk of latrine dysfunction and their pit overflowing. Thus, due to the lack of as-designed use of ADPs, an argument could be made that current recommended ADP practices are impractical or at least do not match with Cambodian households' desires when managing their FS. Household behavior change will be needed to improve the safety of FSM practices. The

absence of Cambodian government regulation or enforcement of safe household sanitation results in all household FSM being essentially voluntary, further limiting the potential impact of FSM solutions that depend on household behavior, like the ADP.

Certain results of this study related to flood proneness are important to consider with regard to achieving SMS in climate-vulnerable regions. Flood-prone households were more likely to have switched their pits likely because their pits filled more frequently due to flooding, which is increasing due to climate change).[18] Also, flood-prone households typically did not perform FS treatment as often, which is consistent with the literature: flood proneness increases challenges related to latrine functionality and can increase unsafe FSM practices to improve or restore functionality.[18] Climate vulnerability, particularly flooding, is thus closely linked with household sanitation behaviors

Findings from this research indicated that the knowledge, education, and experience of households does not necessarily lead to safer sanitation practices. Education level did not positively correlate with safer sanitation practices; however, if more households had higher levels of education, this association may need to be investigated again. Additionally, households that experienced more pit-overflow events typically performed recommended emptying practices less frequently.. Desensitization and increased comfort dealing with FSM (despite doing so unsafely) may explain this finding. These concepts of comfort and familiarity influencing practices with FSM have been reported in the literature.[12] It can be generally inferred that other factors beyond education and knowledge will be necessary to motivate safer household FSM practices.

Limitations

The results of this study are subject to some important limitations. Social desirability bias likely occurred during surveying. Particularly given questions about sensitive or taboo topics like sanitation, respondents tend to provide answers that they view as more socially acceptable to the enumerator but may be less accurate. Social desirability bias was mitigated by enumerators having a brief discussion with participants about why talking about such topics is important to improve public and environmental health. All participants were also reminded that they did not have to give a response to any specific question.

Similarly, recall bias, which describes how respondents may remember past events inaccurately, likely affected responses in this study, particularly regarding whether and how lime was applied to a pit nearly two years prior. Recall bias was minimized by shortening recall periods, using cued recalls, and using landmark events (e.g., the rainy season) instead of calendar dates when possible throughout the survey.

The well-documented lack of service providers in rural Cambodia likely also affected responses to questions that were used to calculate the Emptying Practices index.[9,21,22] For example, households likely emptied their pits themselves (i.e., did not hire a service provider) with buckets or pumps (i.e., not with a vacuum truck) and pierced their pits more frequently due to a lack of ability to hire a trained service provider to empty their pit using safer methods. Thus, the

availability of service providers, which varies across different districts and provinces, likely affect the results of this index and the results reported with this index.

Lastly, a systematic behavior bias was introduced into the study design by the sampling frame. The selected sample specifically included only ADP customers who had used their ADPs between two and four years, and who had experienced FSM on some level (e.g., emptied their pit, switched their pit). Therefore, this study may describe a group of people that are different from the typical Cambodian rural population. Household demographics were used to ensure that the sample population matched the target population of all rural households in Cambodia; however, unmeasured or unknown data may have introduced a systematic bias that cannot be detected.

5. Sector Recommendations

The results of this study provide a detailed picture of the perceptions, practices, and experiences of households with their ADPs and FSM in rural Cambodia. From these results, we can make recommendations to improve ADPs, rural FSM and the rural sanitation sector in general.

When designing FSM solutions, both technical (treatment and disposal) and behavioral (household practices around technology/service) aspects must be considered.
Safely managed rural sanitation is affected by many factors, including technical appropriateness and household practices. Even if two years of storage treatment with lime had inactivated pathogens sufficiently across all tested pits, sustained household SMS would not likely be achieved in rural Cambodia due to unsafe household ADP practices. Households did not show clear understanding, prioritization, or value of FSM, and the risks that improper management of their fecal sludge poses to them, their families, and their communities. Although distributing leaflets to educate households around these issues did occur with this sample, most studied households did not follow recommended practices, increasing the risk of pathogen exposure to themselves and their communities.

Improved and expanded interventions are needed to reduce product and service costs, improve convenience, and more closely ingrain household practices in the design of FSM products and services. Supplementary interventions should support in driving safer household FSM practices, incorporating drivers informed by behavioral science and education on health risks and appropriate sanitation system use and maintenance. When designing new FSM solutions, the sector must consider the level of household FSM knowledge in a specific context and identify where education gaps need to be filled to complement product and service design. Alone however, education is unlikely to drive safe FSM. For example, based on the findings of this study, iDE updated the household leaflet instructions by targeting unsafe behavior change, emphasizing the need to empty the old pit before switching pits, bringing caution about using the pits content as fertilizer before three years of storage treatment (Figure S3). Lastly, clear government standards and enforced regulations around FSM, which is lacking in rural Cambodia, could be a critical milestone to achieve in order to impact household and service providers FSM practices and sustain SMS at scale.

Recommended practices and product/service designs should be adjusted to better match the desires of Cambodian households when managing their FS. Because most households did not

follow recommended ADP practices, the motivations behind this choice must be identified to improve the design of on-site sanitation systems and match the desires of Cambodian households when managing their FS while still achieving on-site FS treatment. For example, because all households did not wait the WHO-recommended two years before emptying their pits, a faster treatment scheme (e.g., using high-dose lime over a few weeks) could be a practical approach to on-site FS treatment with ADPs; this recommendation was also made in the companion article to this article.[15]

Increase access to affordable, trained service providers. Close to half of all households reported that they manually empty their latrine pit themselves, many of them using a bucket. When this is done, waste is generally dumped close to living areas or bodies of water without treatment. When asked why they did not empty and transport waste according to recommended practices, the most common reasons provided were a lack of available materials or a lack of available services. Other studies have highlighted this issue and have found that service providers do not exist, households do not know how to contact them, or they are unaffordable.[9,13,21,22] Increasing access to reliable, safe, and affordable FSM service providers will allow households to safely empty and switch their pits, and dispose of waste, even if there are pathogens present.

Develop more practical tools to easily, accurately, and affordably monitor progress towards access to sustained safely managed sanitation in rural areas including household practices. The results of this study highlight that current SMS interventions and monitoring methods should continue being evaluated and improved to ensure that SDG6 goals are accomplished.[23] Findings of this study indicate that household investment in safe basic sanitation (a single pit pour flush latrine) in addition to onsite FSM technology (ADP) rarely translated to *sustained* safely managed sanitation. The rate of sustained SMS is unknown in Cambodia, and there is a general lack of means by which to identify and classify sustained SMS at the household level. More affordable, practical SMS monitoring tools are needed to appropriately gauge progress towards achieving continuous public health gains as a result of improved sanitation. When conceptualizing safely managed sanitation monitoring, the following dimensions should be included: 1) assessment of household knowledge, preferences, intentions and behaviors; 2) household-driven monitoring to prevent unsafe decision-making and prompt, timely action; 3) evaluation of product/system functionality and effectiveness, especially in areas that are most affected by climate change (e.g. flood-prone areas); and 4) indicators of clearly unsafe sanitation (e.g., open discharging pits).

Households themselves are often unable to assess their own sanitation risk. Tools for households to feasibly monitor their own sanitation situation, like Pit Gauges, should be refined, mainstreamed, and coupled with educational and behavioral interventions that emphasize self-monitoring and system maintenance.

Improve household and private sector compliance with recommended practices via increased financial investment, accountability, and enforcement from local governments around rural FSM. Improved government regulations and strict enforcement, both of which require considerable investment, will be required to ensure that households and the private sector follow safer FSM practices. While the responsibility of increasing access to improved FSM products and services can continue to be borne by the private sector in rural Cambodia, the public sector is needed to develop and enforce regulations to ensure that the benefits of SMS are actually

achieved. These issues must be considered to achieve sustained SMS in rural Cambodia and must be a primary focus of future sanitation development.

Consider and design for climate change and vulnerabilities based on local contexts. Climate change is likely to increase FSM challenges, particularly in climate-vulnerable regions.[18] The results of this study indicate that there is a need for practical, household-level tools to identify where sanitation products including ADPs are appropriate and not. There is also a general need for low-cost, accessible FSM solutions that are appropriate for climate-vulnerable environments, especially those that are flood prone.

For public health to continue to improve via safely managed sanitation, household perceptions, practices, and experiences must be understood and considered when designing on-site sanitation systems. The results of this study highlight that current SMS interventions and monitoring methods should continue being evaluated and improved to ensure that SDG6 goals are accomplished.

6. Acknowledgements

This study was supported by the Australian Government under the Water for Women Fund and implemented by iDE and Causal Design Inc. This study was also made possible in part by the support of the American people through the United States Agency for International Development and Stone Family Foundation. The authors would like to thank iDE Cambodia for leading the design and implementation of this study; iDE Global staff for providing expert feedback in WASH and evidence & analytics; Causal Design Inc. for managing all aspects of the study; Andy Robinson for his continuous feedback throughout the study and reviewing this article; Water WISER and Cranfield University, specifically Alison Parker, Francis Hassard and Barbara Evans, for their feedback on the preliminary study design and research questions; Joe Brown for guidance on the study design, specifically regarding the biology of ADPs; and Mimi Jenkins for support and encouragement with the genesis of this research initiative.

7. References

1. Sanitation | JMP [Internet]. [cited 2019 Mar 8]. Available from: https://washdata.org/monitoring/sanitation
2. United States Environmental Protection Agency. Standards for the Use or Disposal of Sewage Sludge, Final Rules. Volume 58, No. 32 [Internet]. 1993. Available from: https://www.epa.gov/sites/default/files/2020-02/documents/fr-2-19-1993-sewage-sludge.pdf
3. European Commission. Evaluation of sludge treatments for pathogen reduction [Internet]. 2001. Available from: https://ec.europa.eu/environment/archives/waste/sludge/pdf/sludge_eval.pdf
4. Still D, Foxon K. Tackling the Challenges of Full Pit Latrines [Internet]. South Africa: Water Research Commission; 2012. Available from: https://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/1712
5. JMP. Monitoring safely managed on-site sanitation (SMOSS): Synthesis of lessons from phase 1 pilots and recommendations for phase 2 pilots. 2021.
6. Saxena S, Den W. In situ treatment technologies for pit latrines to mitigate groundwater contamination by fecal pathogens: a review of recent technical advances. J Water Sanit Hyg Dev [Internet]. 2021 Dec 20 [cited 2022 Dec 9];12(1):102–15. Available from: https://doi.org/10.2166/washdev.2021.184
7. Strande L, Ronteltap M, Brdjanovic D. Faecal Sludge Management – Systems Approach for Implementation and Operation. Water Intell Online [Internet]. 2014 Jul [cited 2020 May 21];13. Available from: https://iwaponline.com/ebooks/book/384/
8. World Bank. Household Pit Emptying and Reuse Practices in Rural Cambodia [Internet]. World Bank; 2019 [cited 2020 May 21]. Available from: http://elibrary.worldbank.org/doi/book/10.1596/33421
9. Harper J. Fecal Sludge Management in Rural Low-income Cambodia: A review of current knowledge. 2019.
10. Ministry of Rural Development, Kingdom of Cambodia. National Faecal Sludge Management Guidelines for Rural Households [Internet]. 2020. Available from: https://snv.org/assets/explore/download/cambodia-national-fsm-guidelines-eng-21032020.pdf
11. Harper J, Bielefeldt A, Javernick-Will A, Veasna T, Kozole T, Nicoletti C. Household Acceptance of Safe Fecal Sludge Management Practices in Rural Cambodia. Manuscr Prep. 2021;
12. Harper J, iDE Cambodia. When Rural Latrine Pits Fill: Characterizing Household Choices and Encouraging Safe Fecal Sludge Management [Internet]. FSM5; 2019; FSM5. Available from: https://drive.google.com/open?id=14QxLBR8JQ3RBMt1R40yXrQeaB7Fu6iTx
13. Kong M, Bartell J. Behavioral drivers of fecal sludge management in rural Cambodia: A qualitative study (technical report). WaterSHED; 2018.
14. World Health Organization. Guidelines for the safe use of wastewater, excreta and greywater - Volume 4 [Internet]. WHO. 2006 [cited 2018 Jul 11]. Available from: https://www.who.int/publications/i/item/9241546859
15. Harper J, Abdel-Sattar R, Kozole T, Veasna T, Rogla J, Ross M, et al. Microbial Hazards in Real-world Alternating Dual-Pit Latrines Treated with Storage and Lime in Rural Cambodia. Submitt Publ. 2023;
16. Solutions IRB [Internet]. Solutions IRB. [cited 2022 Dec 8]. Available from: http://www.solutionsirb.com/

17. MRD. Identification of Poor Households (IDPoor) Programme [Internet]. Ministry of Rural Development, Kingdom of Cambodia. 2019 [cited 2020 May 22]. Available from: https://mop.idpoor.gov.kh/
18. Abdel Sattar R, Rogla J, Veasna T, Kozole T, Nicoletti C, Harper J. Effects of Climate Vulnerability on Sanitation Access, Sanitation Infrastructure Functionality, and Households' Sanitation Practices in Rural Cambodia. Manuscr Prep. 2023;
19. iDE Cambodia. Waste Management Pilot Project, End of Project Report [Internet]. 2011. Available from: https://drive.google.com/open?id=1f_6aN-0wrDyT8v2O4jqyxR6p19GntfeW
20. Ajzen I. Perceived behavioral control, self-efficacy, locus of control, and the theory of planned behavior. J Appl Soc Psychol. 2002;32(4):665–83.
21. USAID and PSI-PSK. Sanitation Market Landscape in Cambodia, Desk Review [Internet]. 2017. Available from: https://drive.google.com/open?id=1bASKfqqymQ5Y3E2an8n8_AdFV0x04ca2
22. SNV. Beyond the Finish Line in Cambodia: Sustainable Sanitation and Hygiene for All (SSH4A Phase III): Faecal Sludge Management (FSM) Research Report [Internet]. 2019. Available from: https://drive.google.com/open?id=1B2ihcp0Ip7ZHGz8bpHY8J1d-NTHWyraP
23. UN. Status and Trends of Progress of SDG 6, Highlights. 2018.
24. UNICEF/GWP. Strategic Framework on WASH Climate Resilience [Internet]. [cited 2023 Jan 19]. Available from: https://www.gwp.org/en/WashClimateResilience/
25. UN WFP. Cambodia Flood Extent in 2011 [Internet]. 2011 [cited 2022 Jun 13]. Available from: https://geonode.wfp.org/layers/geonode%3Akhm_nhr_floods_unosat_2011
26. World Health Organization, editor. Sanitation safety planning: manual for safe use and disposal of wastewater, greywater and excreta. Geneva: World Health Organization; 2015. 138 p.
27. Harper J, Bielefeldt A, Javernick-Will A, Veasna T, Nicoletti C. Context and intentions: practical associations for fecal sludge management in rural low-income Cambodia. 2020;11.
28. Liu H Tao. Achilles heel of environmental risk from recycling of sludge to soil as amendment: A summary in recent ten years (2007–2016). Waste Manag [Internet]. 2016 Oct 1 [cited 2020 Sep 28];56:575–83. Available from: http://www.sciencedirect.com/science/article/pii/S0956053X16302604

8. Supporting Information

Installation Manual and Technical Guidelines of ADPs provided by iDE

The Installation Manual for ADPs is available at https://bit.ly/3QKm0hl, and the Technical Guidelines for ADPs are available at https://bit.ly/3Zsy5vH.

Inclusion Criteria

All households included in the study met specific inclusion criteria, which were determined by asking each household, since the installation of the ADP:

- Has the pit filled or overflowed?
- Has the pit been pierced[1] or modified for fluid discharge?
- Has the pit been emptied, either partially or completely?
- Has the pit been switched from the new pit to the old pit?
- Is the toilet offset, and were the pits installed in parallel?

If a household member answered "yes" to any of the above questions, they were given the behavioral survey in person by research assistants, who are full time trained staff of iDE's monitoring and evaluation team.

Behavior Survey

The complete behavior survey was created in Taroworks and is available at https://osf.io/uwq82/.

Household Demographics and Socio-economic Characteristics

This section provides an overview of key demographic characteristics represented by the sample. The survey was administered to a total of 1,103 households distributed across five of the 25 Cambodian provinces (Siem Reap, Kampong Thom, Kandal, Prey Veng, and Svay Rieng). These five provinces were selected as target areas for this research as iDE-connected businesses are manufacturing and installing ADPs at scale across these provinces. Furthermore, these provinces were selected because their geographic and demographic disparities ensure that results are both regionally specific and representative of the broader Cambodian context. Out of 1,103 households, only 770 households were eligible and consented to participate in the study with a response rate of 100%.

Of the 770 households surveyed, a majority of the households (25% each) were from Svay Rieng and Prey Veng provinces, followed by 20% of the households from Kampong Thom (Table S9). Approximately 18% and 12% of the households were from Siem Reap and Kandal provinces, respectively.

While the survey tool did not explicitly capture the gender of the household head, it asked about the gender of the respondent. Almost two thirds of respondents (63%) were women. The likely

[1] Pit piercing is the practice of installing a hole or overflow pipe into the top ring of a pit to allow liquid FS to drain out of the top of a pit when it becomes nearly full. FS then drains into nearby bodies of water, onto open land, or into additional pits or tanks. Pit piercing is an unsafe practice because it contaminates the environment and typically exposes households and communities to harmful pathogens.

reason for a higher number of women involved in the survey was the absence of men in the house due to working duties.

Published research indicates that households living in climate-vulnerable, flood-prone areas are more likely to practice unsafe FSM behaviors as a result of increased challenges with latrine functionality caused by frequent occurrences of premature pit filling.[24] Within the context of rural Cambodia, a household is considered to be climate vulnerable if they are living in flood-prone areas that are faced with higher frequency and severity of climate shocks (e.g. major flood events, heavy rainfall events), where a flood prone area in this study was defined by satellite data of a 2011 major flood event.[18,25] About 70% of the sample (540 households) live in an area identified as flood-prone. The high fraction of households living in flood-prone areas can be explained by the fact that the majority of communities in the five target provinces are located in close proximity to water bodies (e.g. lakes and rivers). This is common in rural Cambodia and indicates that climate vulnerability is a mainstream issue for the majority of ADP customers. Where relevant, results are disaggregated by geography and community vulnerability to flooding.

A relatively small fraction (6%) of all households surveyed were identified as poor (either IDPoor 1 or ID Poor 2) according to this method of classification.

The highest level of education achieved could also influence preferences for FSM-service attributes in rural Cambodia. The majority (66%) of households in the sample reported that at least one household member had completed secondary school. Approximately a fifth of all households (21%) reported at least one member with a university degree, while only 12% of households reported that primary school was the highest level of education received by any member.

Across the entire sample, households reported that their latrine was used by an average of approximately eight people in total. The majority (63%) of households reported that they did not share their latrine with anyone outside of their household. The average number of users within the household was approximately six. The remaining 37% of households reported sharing their latrine with household members as well as an additional five individuals from outside the household.

While there are different kinds of latrine designs, the majority of latrines used across rural Cambodia are either single pit latrines or dual pit latrine systems. Dual pit latrines can have pits in series or in parallel (i.e., alternating dual pits), and both provide improved functionality and FS storage capacity.[7] Pits in series provide increased aerobic decomposition of FS and increased soil infiltration rates for liquid FS, and ADPs provide on-site treatment by allowing FS within a pit to be left undisturbed for at least two years, during which time pathogens die-off sufficiently to allow households to empty their own pits with decreased health risks.[26]

As ADPs are an improved product, all ADP owners were expected to have had an existing toilet/latrine pit on their property prior to the installation of the ADP. Of the 770 households surveyed, 99% reported that they had at least one existing pit prior to installation of the ADP, with only five households reporting that they did not know if they had had an existing pit. The

majority of households (70%) reported that they had only one pit at the time the ADP was installed.

Households who reported that they had at least two pits prior to the installation of their ADP were asked if they had connected their old pit to the new ADP pit to form a series. The majority of households (99% or 222 households) reported that they had connected their old and new pits. Of these households, 88% reported that they had only connected a single pit. Based on these results, for households that own existing pits in series, it is highly likely that they will not alternate between ADP pits but rather revert back to pit in series.

Of households whose pits were connected in a series, the majority reported that their old pit had one to three concrete rings underground. About 70% of the households' pits were equipped with three concrete rings. The number of concrete rings is an indicator of the total volume of the pit(s) of a latrine, which is constructed with stacked concrete rings in a dug up pit underground. A greater number of concrete rings increases the volume of fecal sludge a latrine containment system can hold, suggesting a longer period before pit fill.

ADP Experiences

Pits Filling

Most households (91%) had experienced their new pit filling or overflowing since their ADP had been installed; this result confirmed the intended sampling frame. Most households (85%) had experienced their new pit filling/overflowing 1-3 times; however, 9% and 5% had experienced their new pit filling/overflowing 4-10 and 10+ times, respectively. Among households who experienced their pit filling at least once, pit fill was most commonly reported between the months of July and November (Figure S7), which coincides with the rainy season in Cambodia, which generally begins in May and ends around September. The heaviest rainfall usually occurs in August and September, which were also the months with the highest reported pit fill rates; this result suggests that pits filling is closely tied to rainfall and associated flooding.

Household members were able to determine when their pit filled using different methods. The most common method was using their Pit Gauge (49%; n = 770). Households also cited a variety of other, less formal methods for recognizing a full pit, including the latrine not flushing (41%), waste spilling out (28%), and an odor coming from the pit or latrine (21%). However, only approximately 10% of households reported switching their pit because their Pit Gauge indicated that it was time to switch, suggesting that most households waited until the pit was filled above the recommended level before switching their connection.

Maintenance Challenges

To better understand the challenges that households faced when using the ADP, households were asked about the primary maintenance issues they encountered when using the latrine (n = 770). The majority of households (76%) reported that their pit filling or overflowing was a substantial problem. Additionally, 37% of households reported that the system has a strong odor, and 33% reported that their toilet regularly would not flush (likely another sign of pit overfilling). Some of the other reasons included a toilet requiring too much water to flush, flooding, difficulty in emptying the pit, the cost to empty the pit, cracked pit lid etc.

Possible justifications for these findings include 1) the fact that iDE is more likely to sell ADPs to people whose existing latrine pit has filled up prematurely because they live in environments with dense and saturated soil (e.g. clay), high groundwater table, and/or flooding; 2) an iDE ADP upgrade may be installed too close to the original pit (i.e., less than the 1.35-m design standard), causing a reduced infiltration zone for the new pit due to clogged soil around the old pit or other ADP system installation issues; and/or 3) the pit is full due to other variables such as household size.

Of the households who reported they had emptied their pit, the majority (63%) reported experiencing no problems with the pit emptying process. Among households that did face challenges, an unpleasant smell was the most commonly reported issue (20%). To a lesser extent, households also struggled with waste being difficult to remove due to the consistency (sludge was too dry or too wet) and logistical issues accessing the pit.

Household Practices Compared to Recommended Practices

Households reported various reasons for reconnecting their toilet to their existing limed pit in their ADP (n = 219): new pit was full (89%); latrine would not flush (25%); Pit Gauge indicated that it was time to switch (9%); pit was almost full or full (8%); needed to prepare for the rainy season (4%); and other (8%).

Households waited different numbers of months before emptying their pit that was undergoing storage and lime treatment (n = 46): 20% waited less than 6 months; 39% waited 6 to 12 months; 26% waited 12 to 18 months; and 9% waited 18 to 24 months. No house reported waiting 24 months or longer.

Recommended practices state that when pit switching, the pit that has completed storage and lime treatment should be emptied by a household member emptied and the FS it contained used as fertilizer. However, 173 of 770 households reported not emptying this pit for different reasons: more space was available in this pit (51%); a service provider was not available (16%); and decided to install another pit instead (16%).

Pit Piercing

A total of 34% (n = 263 of 770) of all households pierced their pits. While this statistic is not generally representative of ADP customers due to the eligibility criteria of this survey, this is certainly an unsafe household practice that needs to be mitigated to achieve progress towards SMS.

Pit piercing practice were relatively common in Svay Rieng (62%) and Prey Veng (43%) provinces (Table S10). Living in climate vulnerable flood-prone areas can exacerbate households' unsafe FSM intentions and behaviors. Households living in flood-prone areas pierced their pits at higher rates (36% versus 29% among households in non-climate vulnerable communities). This result is consistent with the literature, which states that households that experience flooding or have older latrines practice pit piercing more often than the households that do not live in flood-prone areas.[12]

Pit Emptying and Sludge Disposal

To understand how households' context affects their FSM practices, the survey asked the households: "What steps did you take when your new pit filled up or overflowed?" The responses to this question can be categorized as either "desirable" or "undesirable" FSM practices. Desirable FSM practices were deemed to be those held by latrine owners who managed their FS safely by either paying for professional emptying services or by installing a new pit.[27] Within this study, desirable FSM practices provide an opportunity for safe FSM; for example, paying for professional emptying provides the opportunity for safe FSM because regulating FSM service operators is at least possible, while regulating how every household empties their own latrine is effectively impossible. Undesirable or unacceptable practices included pit piercing, self-emptying, stopping latrine use, and doing nothing.

When asked about what they did the last time their pit filled, households typically changed their latrine connection to their old pit (i.e., followed iDE recommended ADP protocols; 26%); did not do anything to address the issue (21%); or pierced their new pit (15%; Figure S8).

Changing the latrine connection to the old pit was more common in flood-prone areas, where 31% of households reported using this as a mechanism for addressing a full pit (compared to 23% of households in non-flooded areas; Figure S9). Pit piercing and connecting the old pit to a new pit were also slightly more common (4% and 3%, respectively) in flood-prone areas. Households in flood-prone areas were also reported emptying their pit fully at slightly higher rates and were less likely to 'do nothing' about a full pit than households in non-flooded regions.

Overall, however, the share of households who report emptying their pit after it fills remains low. Only a fifth (20%) of all households who experienced pit filling reported emptying their pit, which is defined as the emptying of a significant amount of sludge for long-term use of the latrine.

The pit emptying process begins with the household's identification that their latrine is full and that it needs to be emptied. Depending on the availability of disposal area, the household addresses the issue by either finding a pit emptying service provider or conducting the emptying independently. Availability and price of the service provider as well as their skills and equipment are some of the other important factors that the household considers before emptying their pit

Among households who both emptied their pit and reported that they had not yet changed their connection (107 households or 14% of the sample), the majority (54%) reported that a household member had emptied the old pit themselves. Using a service provider was also a common choice, with 42% of households reporting they had sought professional help to empty their pit.

Regardless of who is emptying the pit, it is important that safe pit emptying practices are applied. This includes using the proper equipment and safety techniques to prevent the release of untreated FS into the environment. The three possible methods for emptying pits include: Manual emptying, mechanical emptying, and using a vacuum-truck. Manual emptying is performed using buckets, hoes, shovels and sticks to remove FS from pit latrines. Mechanical

emptying uses agricultural or sludge pumps and piping to empty only liquid FS from pits and tanks. Vacuum trucks empty a pit using suction and transport FS in a large on-board tank.

Among households that have conducted pit emptying, 36% of them hired a vacuum truck to empty the pit. Most households reported emptying their pits using unsafe practices and the use of pumps for mechanical emptying were less common. About 60% of the households conducted pit emptying themselves either manually (37%) or mechanically (24%) (emptying their own pit with lack of proper equipment, training, treatment, or safe disposal site). They preferred self-emptying because they did not have to rely on anyone outside of their household (e.g., a service provider) to manage their FS. Overall, hiring a vacuum truck and self-emptying using a shovel/bucket were the two most popular pit emptying practices in the rural areas. Previous understanding of rural FSM needs was that pit emptying services provided by vacuum trucks are usually dismissed by households due to high prices. The popularity of this method of emptying pits suggests this is not the case, but this study did not specifically gather data around the price points of each emptying mechanism.

Households empty their pits for many reasons, the most common being that the pit was overflowing (71%; n = 76 of 107), followed by the latrine being unusable or was no longer flushable (40%), foul smell coming from the pit regardless of its functionality (33%), and to fertilize crops (12%).

Transportation and Disposal of Fecal Sludge

The most common method for transporting fecal sludge was reported to be by vacuum truck, which was used by 42% of households who emptied their pit (n = 45 of 107) and is generally considered to be the safest available method of transporting FS. Another common mode of FS transport reported by households was carrying the sludge on foot using buckets or sacks (36% of households). An additional 19% of households reported using other methods for transporting FS, which generally consisted of using a hand cart, and only 4% transported FS on a bicycle, motorbike or tractor.

Approximately 40% of the households reported transporting FS to a site within a one-minute walk of the pit, their house, or a nearby water source (i.e., on their property where household and other community members might be exposed to it). Only about a quarter of households (23%) disposed of their fecal sludge farther than a one-minute walk from their pit, a water source, or their home. Approximately one in three respondents (30%) did not know where their household's FS had been disposed of.

The literature suggests that FS disposal locations that are deemed acceptable to Cambodian households include crop fields, which may have significant public health effects.[28] Moreover, households with unsafely managed sanitation practices tend to select disposal locations within or nearby their communities. Of the total 107 households who emptied their pits, about 33% of those reported disposing FS onto their own field as a fertilizer, followed by 8% of those reported disposing FS in a body of water, about 7% reported disposing FS on household property (for composting) as waste. About 33% of the households reported they were unsure about where FS is disposed.

Figures

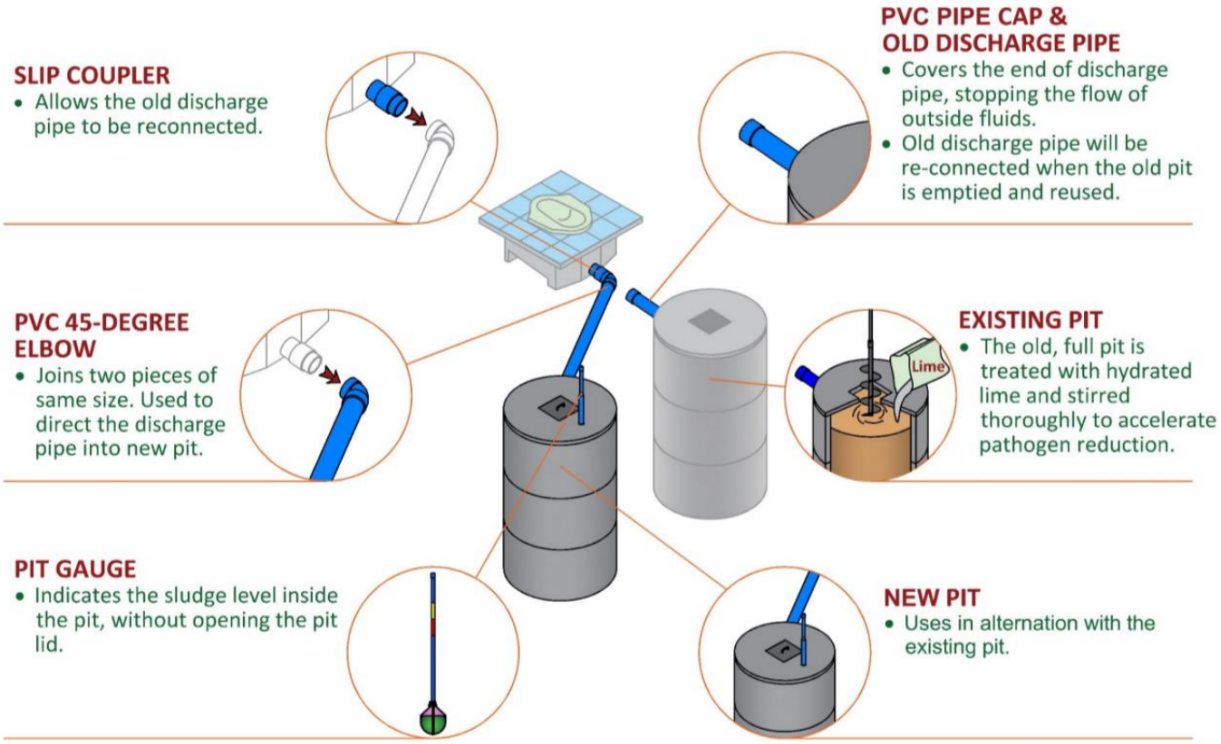


Figure S1: Product details of alternating dual-pit upgrade provided by iDE to rural sanitation businesses in Cambodia

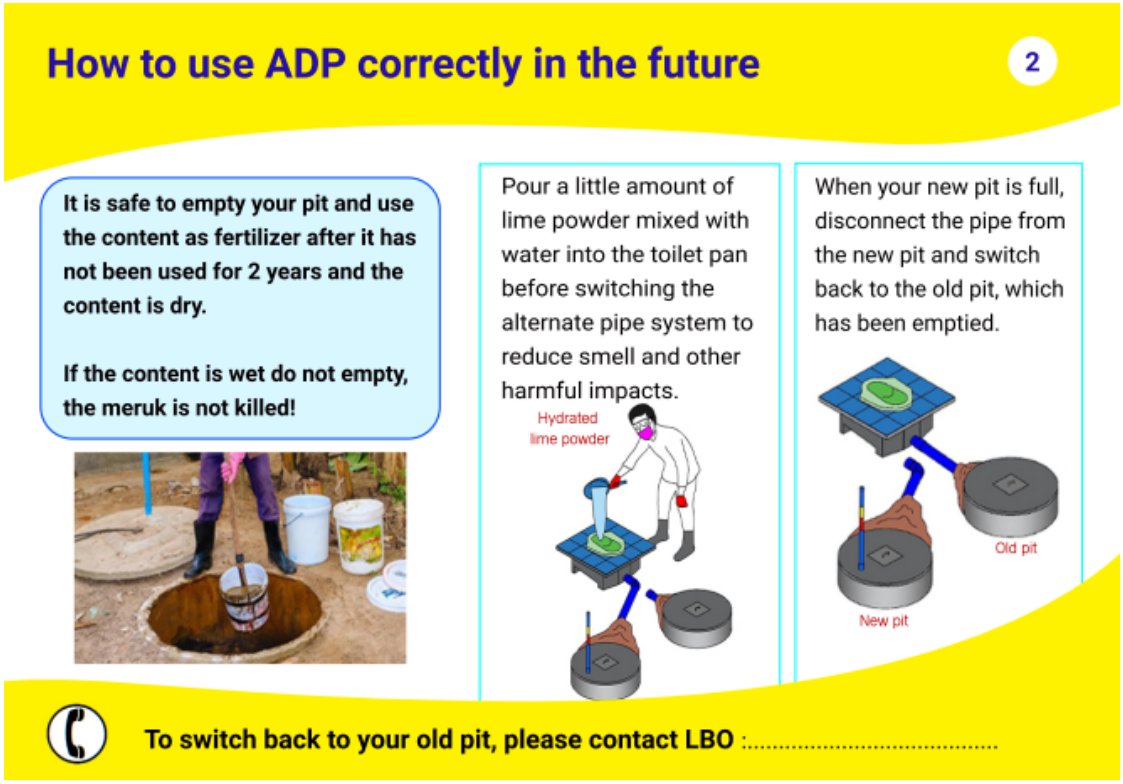


Figure S2: iDE-recommended household SMS practices after the purchase and installation of an alternating dual-pit latrine

Figure S3: Updated iDE-recommended household SMS practices after the purchase and installation of an alternating dual-pit latrine

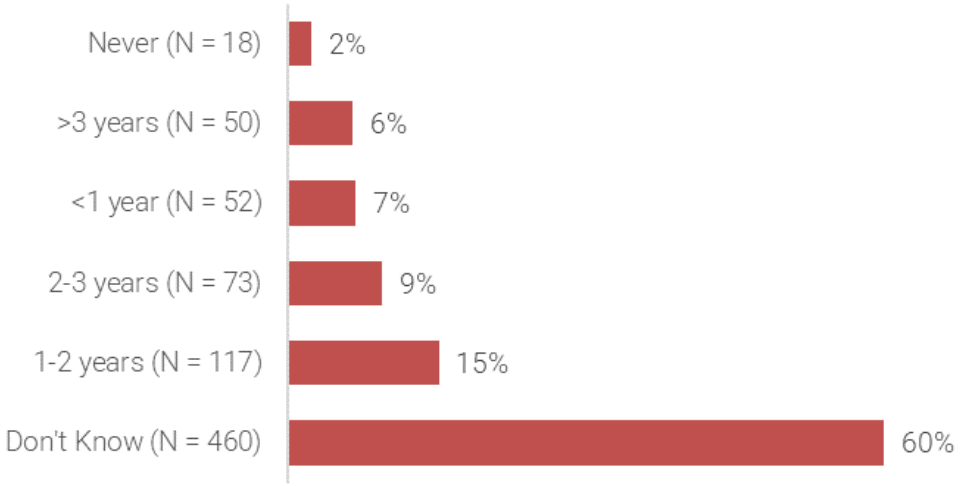


Figure S4: Household perceptions of the duration required before fecal sludge undergoing storage treatment is safe to touch

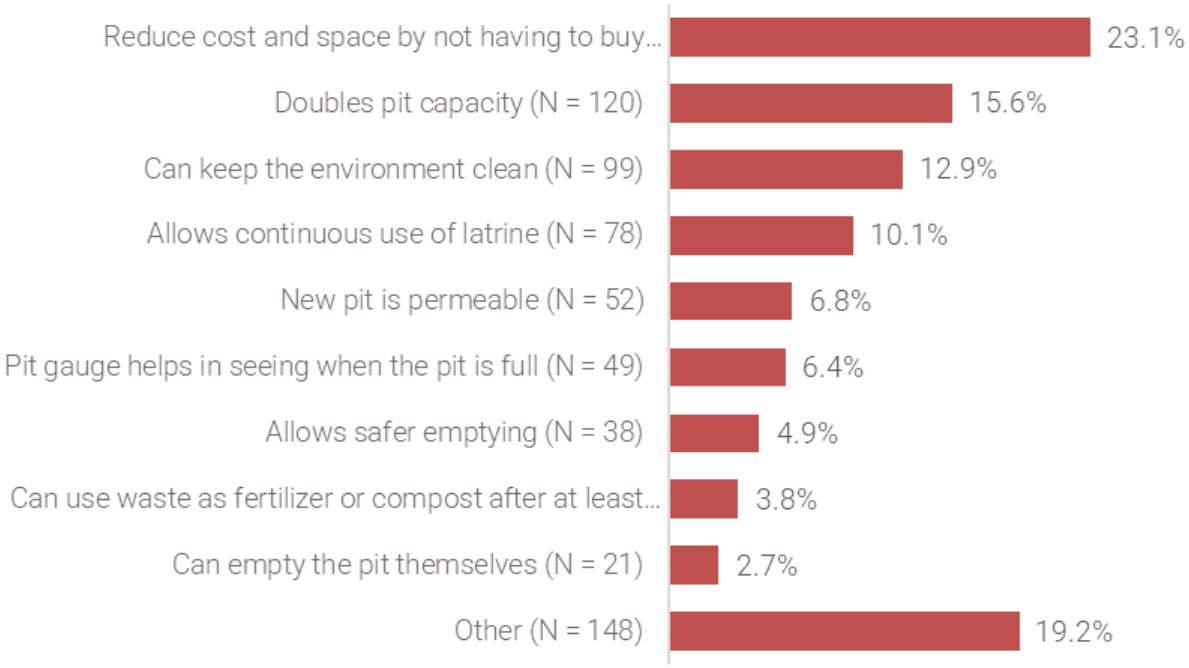


Figure S5: Households' perceived advantages of owning an ADP (n = 770)

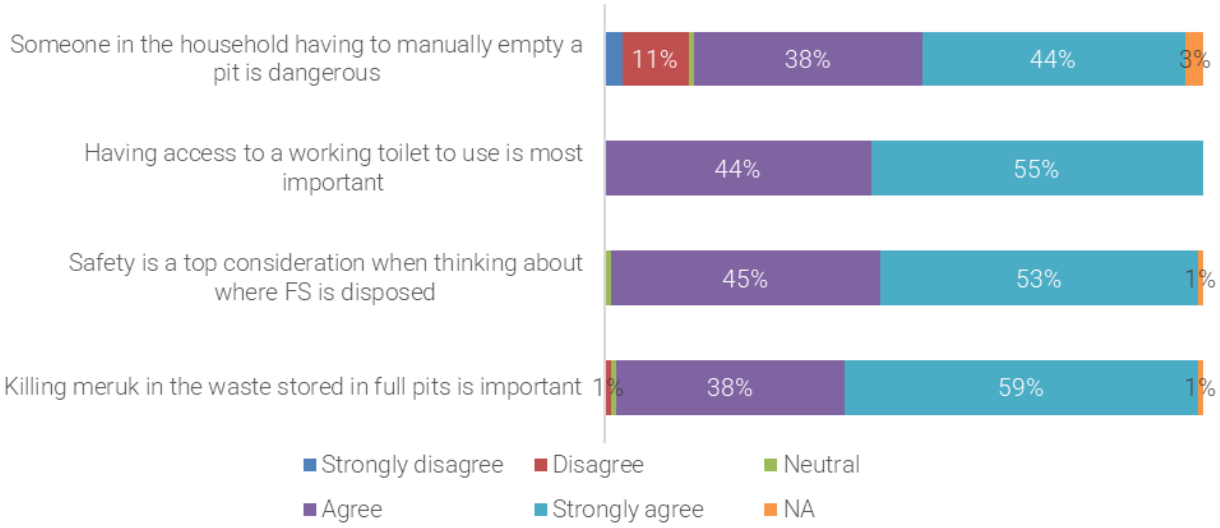


Figure S6. Household perceptions of fecal sludge, toilets, and FSM (n = 770)

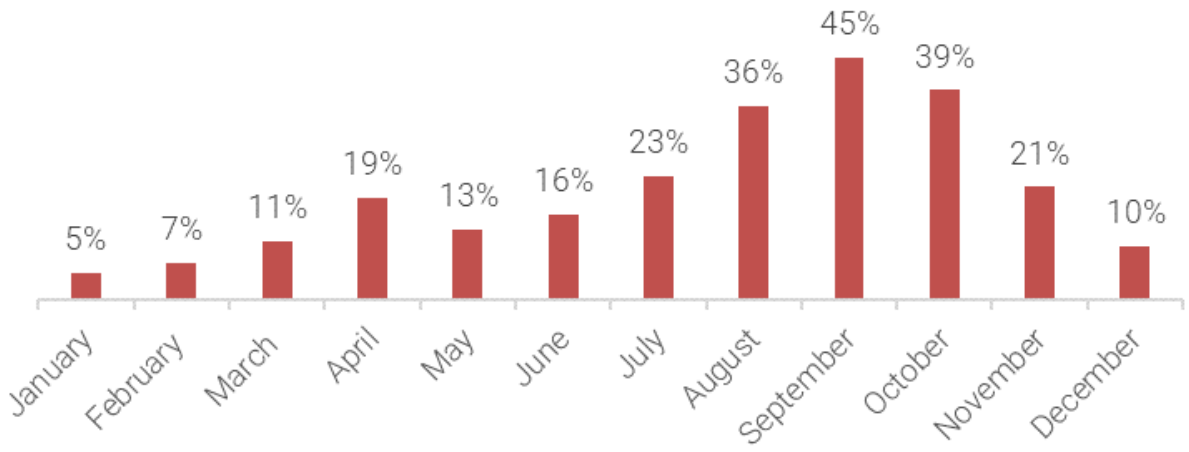


Figure S7: Month in which households' new pit filled (n = 669). Households could select multiple months if their new pit filled more than once.

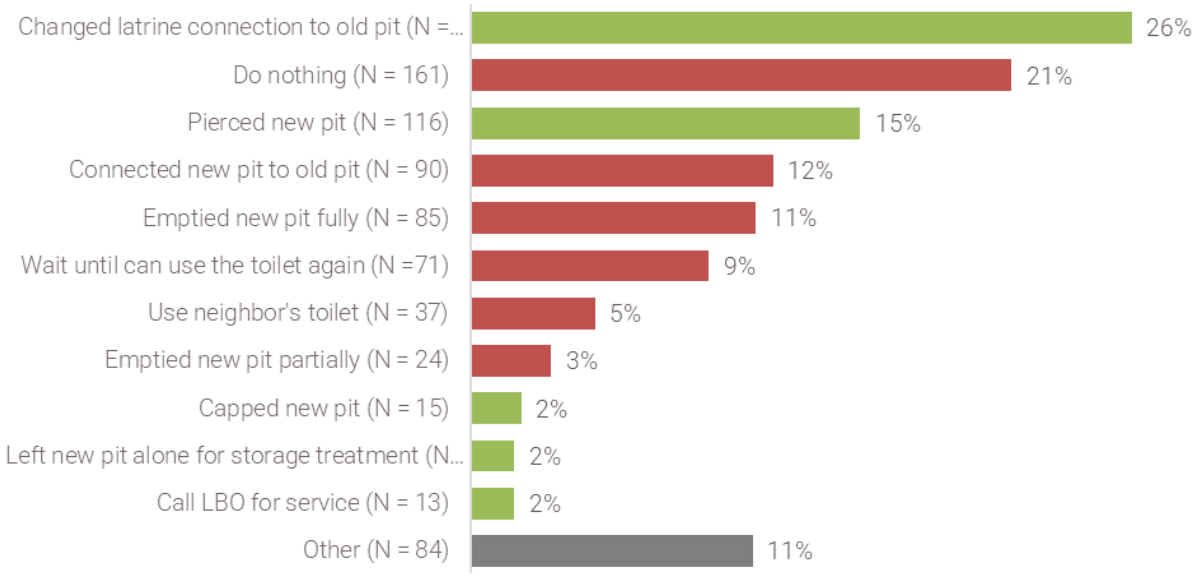


Figure S8. Household practices when their pit filled (n = 770)

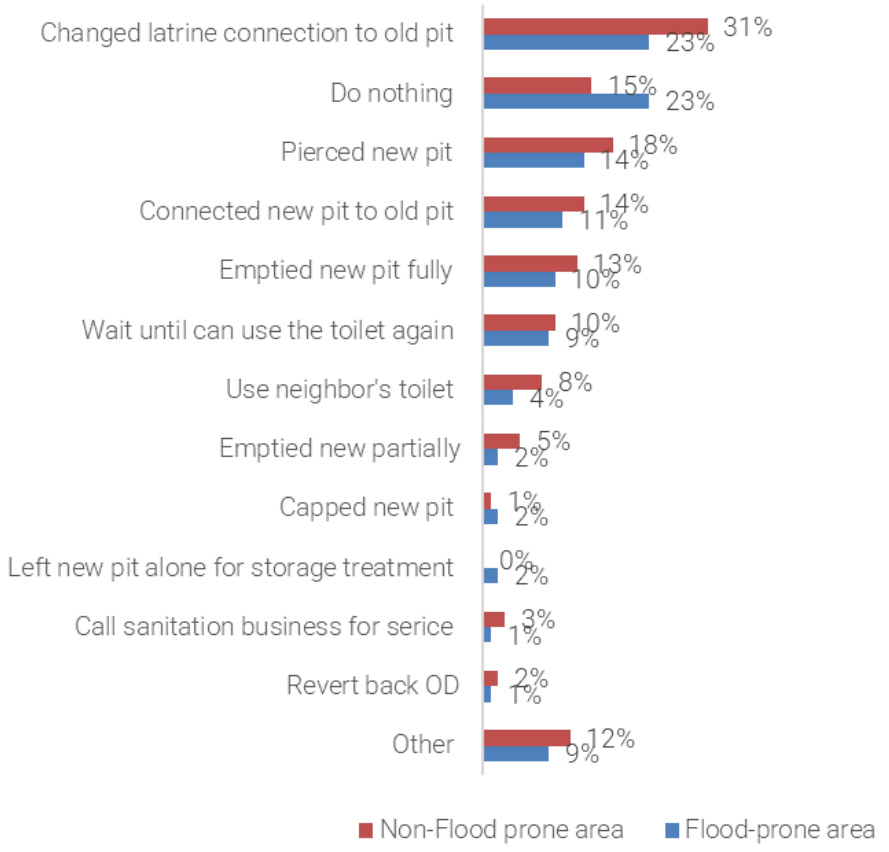


Figure S9. Household practices when their pit filled by flood proneness

Tables

Table S1. Details of sample size calculations for behavioral survey.

Province	Total Number of ADPs that Have Been in Use for ≥ 2 Years	ADPs that Have Likely Filled Since Installation	Calculated Household Sample Size to Achieve Desired Precision
Kampong Thom	1,377	345	151
Kandal	582	146	95
Prey Veng	2,843	711	195
Siem Reap	1,103	276	136
Svay Rieng	2,505	627	188
Total	8,410	2,105	765

Note: A pit fill rate of 25% was assumed across all provinces based on phone survey data.

Table S2. Safe-FSM-practices probability indices with associated questions, possible responses, scores, and score rationales

Index	Question	Possible Responses	Scores	Score Rationale
Emptying Practices	Did the household empty their old pit?	Yes No	0 2	Because all households in this study reported at least one pit fill, emptying their pit when it filled is the first step in selecting a safe FSM practice.
	Who emptied the old pit?	Household member Friend or neighbor Service provider Other	0 0 2 0	Being aware of safer FSM practices (e.g., hiring a trained service provider) is a key component of performing a safer FSM practice. Less safe emptying practices that are typically performed in rural contexts include a household emptying their own pit (e.g., self-empty).
	What methods were used to empty the old pit?	Manually Mechanically Vacuum truck Buried old pit Don't know	0 1 2 0 0	Pit emptying should be performed using specific equipment with proper safety techniques to prevent the release of untreated FS into the environment. Vacuum trucks typically provide the safest emptying of FS. Emptying mechanically (e.g., with a pump and piping) is typically less safe than a vacuum truck due to leaks and exposure to sludge, and emptying manually (e.g., with a shovel) is least safe.
	Did the household pierce their pit?	Yes No or Don't know	0 2	Piercing a pit is a dangerous practice and releases untreated FS into the environment.
	How many months was the old pit left disconnected from the toilet before it was emptied?	< 1 year 1-1.5 years >2 years Don't know	0 1 2 0	Believing that FS can be emptied safely in less than 1 year is dangerous. Understanding that FS becomes safer to empty after 2 years indicates that a household understands how ADPs work.
	Where was the FS disposed of?'	<10-sec walk… <1-min walk… >1-min walk… …from pit, house, or water point Don't know	0 1 2 0	Households tend to select locations within their communities or nearby their houses for FS disposal, which can expose people to the pathogens in untreated FS.
	How was the waste disposed of?	Buried Into body of water Onto field as waste Onto field as fertilizer Into treatment plant Don't know	2 0 0 1 2 0	Safer FSM practices include disposal of FS into a landfill or reused after treatment, typically as fertilizer or fuel.

Pit Switching Practices	When switched pits, was the old pit emptied when the new pit filled?	Yes No	2 0	Households should have emptied their disconnected pit before the new pit filled.
	When switched pits, who emptied the old pit?	Household member Friend or neighbor Service provider Don't know	0 0 2 0	Households should have had their disconnect pit emptied by a trained service provider.
	When switched pits, how many months was the old pit left disconnected from the toilet before it was emptied?	< 1 year 1-1.5 years >2 years Don't know	0 1 2 0	The household should have left the old pit disconnected for a sufficient amount of time (at least two years) before emptying.
	Who switched the pits?	Household member Service provider	0 2	The household should have hired a trained service provider to switch their pits.
	When switched pits, was the old pit disconnected from the toilet until the new pit filled?	Yes No	2 0	The household should have disconnected their old pit from the toilet until the new pit filled.
Treatment Practices	When switched pits, was the pit most recently connected to the toilet treated with lime?	Yes No or Don’t know	2 0	The full pit should have been treated with lime after the connection was switched.
	When switched pits, who performed the lime treatment in the pit most recently connected to the toilet?	Household member Service provider	0 2	Lime treatment should have been performed by a qualified service provider.
	Was any product used to treat the FS in the pit most recently connected to the toilet?	Yes (2) No or Don't know	2 0	Adding a product to treat/kill meruk (substances that cause disease or bad smells) in FS is important.
Sanitation Knowledge	Know that FSM affects health	No Somewhat Yes	0 1 2	Understanding that how pits are managed affects public health indicates more knowledge about safer FSM practices.
	Know that disposing FS into a body of water is unsafe	No Somewhat Yes	0 1 2	Understanding that putting FS in bodies of water is unsafe indicates more knowledge about safer FSM practices.
	Know that disposing FS onto a field is unsafe	No Somewhat Yes	0 1 2	Understanding that putting FS onto fields of water is unsafe indicates more knowledge about safer FSM practices.
	Know that the water that comes out of a pit above ground is unsafe	No Somewhat Yes	0 1 2	Understanding that water from pits is unsafe indicates more knowledge about safer FSM practices.

Sanitation Attitudes	Feels that killing pathogens in FS is important	No Somewhat Yes	0 1 2	Feeling that killing meruk in FS (i.e., treatment) is important indicates more positive attitudes towards safer FSM practices.
	Feels that safety is a top consideration when considering where to dispose of FS	No Somewhat Yes	0 1 2	Feeling that choosing a safe location to dispose FS is important indicates more positive attitudes towards safer FSM practices.
	Feels that a household member emptying a pit is unsafe	No Somewhat Yes	0 1 2	Feeling that it is not right for the HH member to empty the pit because they are not a professional service provider indicates more positive attitudes towards safer FSM practices.

Table S3. Percentages of households that switched their pits by province and flood proneness (n = 770)

	Percentage of households
Province	
Kampong Thom	20%
Kandal	15%
Prey Veng	21%
Siem Reap	36%
Svay Rieng	10%
Flood proneness	
Non-flood prone	37%
Flood-prone	63%

Table S4. Linear Regression Results of the Emptying Practices Index

	Emptying Practices Index	
Variable[1]	**Coefficient**	***p*-value**
Province		
Kampong Thom	-	-
Kandal	0.04	0.5
Prey Veng	-0.20***	0.000
Siem Reap	0.13**	0.02
Svay Rieng	-0.40***	0.000
Flood proneness		
Non-flood prone	-	-
Flood-prone	0.0	0.9
Poverty level (IDPoor status)		
Non-IDPoor	-	-
IDPoor 1	0.3	0.1
IDPoor 2	-0.1	0.4
Unknown	0.15*	0.07
Education		
No formal education	-	-
Primary schooling	-0.20**	0.02
Secondary schooling	-0.15**	0.04
University graduate	-0.1	0.3
Vocational training	-0.2	0.5
# times pit overflowed since ADP installed		
Never	-	-
1-3 times	-0.58**	0.01
4-10 times	-0.61**	0.01
More than 10 times	-0.66***	0.007
Constant	1.6***	0.000
Observations	700	
Adjusted R-Squared	0.12	

1: All coefficients of categorical variables are in reference to the first response indicated (e.g., "Non-IDPoor" and "No formal education"). Thus, all coefficients describe the difference between a given response and the reference response.

* p<0.1; ** p<0.05; *** p<0.01

Table S5. Linear Regression Results of the Switching Practices Index

	Switching Practices Index	
Variable[1]	**Coefficient**	***p*-value**
Province		
Kampong Thom	-	-
Kandal	0.1	0.4
Prey Veng	0.0	0.5
Siem Reap	0.0	1.0
Svay Rieng	0.0	0.9
Flood proneness		
Non-flood prone	-	-
Flood-prone	0.0	0.4
Poverty level (IDPoor status)		
Non-IDPoor	-	-
IDPoor 1	-0.45*	0.08
IDPoor 2	-0.1	0.7
Unknown	0.2	0.4
Education		
No formal education	-	-
Primary schooling[2]	-	-
Secondary schooling	0.0	0.8)
University graduate	0.00	1.0
Vocational training	-0.14*	0.08
# times pit overflowed since ADP installed		
Never	-	-
1-3 times	-0.1	0.4
4-10 times	0.0	0.8
More than 10 times	0.0	0.9
Constant	0.94***	0.000
Observations	211	
Adjusted R-Squared	-0.01	

1: All coefficients of categorical variables are in reference to the first response indicated (e.g., "Non-IDPoor" and "No formal education"). Thus, all coefficients describe the difference between a given response and the reference response.
2: Too few households reported this response and thus, this category was removed from this model.
* p<0.1; ** p<0.05; *** p<0.01

Table S6. Linear Regression Results of the Treatment Practices Index

	Treatment Practices Index	
Variable[1]	**Coefficient**	**p-value**
Province		
Kampong Thom	-	-
Kandal	0.1	0.6
Prey Veng	0.1	0.4
Siem Reap	0.0	0.8
Svay Rieng	0.2	0.2
Flood proneness		
Non-flood prone	-	-
Flood-prone	-0.19**	0.02
Poverty level (IDPoor status)		
Non-IDPoor	-	-
IDPoor 1	1.27***	0.000
IDPoor 2	-0.2	0.3
Unknown	-0.18*	0.06
Education		
No formal education	-	-
Primary schooling[2]	-	-
Secondary schooling	0.1	0.2
University graduate	0.0	0.9
Vocational training	-0.2	0.2
# times pit overflowed since ADP installed		
Never	-	-
1-3 times	0.34***	0.000
4-10 times	0.2	0.2
More than 10 times	0.57***	0.008
Constant	-0.1	0.5
Observations	311	
Adjusted R-Squared	0.07	

1: All coefficients of categorical variables are in reference to the first response indicated (e.g., "Non-IDPoor" and "No formal education"). Thus, all coefficients describe the difference between a given response and the reference response.
2: Too few households reported this response and thus, this category was removed from this model.
* p<0.1; ** p<0.05; *** p<0.01

Table S7. Linear Regression Results of the Sanitation Knowledge Index

	Sanitation Knowledge Index	
Variable[1]	**Coefficient**	***p*-value**
Province		
Kampong Thom	-	-
Kandal	-0.11**	0.04
Prey Veng	0.0	0.4
Siem Reap	0.12**	0.02
Svay Rieng	0.0	0.9
Flood proneness		
Non-flood prone	-	-
Flood-prone	0.1	0.2
Poverty level (IDPoor status)		
Non-IDPoor	-	-
IDPoor 1	0.24***	0.002
IDPoor 2	-0.1	0.5
Unknown	-0.1	0.6
Education		
No formal education	-	-
Primary schooling	-0.21*	0.08
Secondary schooling	-0.2	0.1
University graduate	-0.2	0.2
Vocational training	-0.42***	0.005
# times pit overflowed since ADP installed		
Never	-	-
1-3 times	-0.16*	0.09
4-10 times	-0.1	0.5
More than 10 times	-0.20*	0.08
Constant	1.46***	0.000
Observations	700	
Adjusted R-Squared	0.03	

1: All coefficients of categorical variables are in reference to the first response indicated (e.g., "Non-IDPoor" and "No formal education"). Thus, all coefficients describe the difference between a given response and the reference response.

* p<0.1; ** p<0.05; *** p<0.01

Table S8. Logistic Regression Results of the Sanitation Attitudes Index

	Sanitation Attitudes Index	
Variable[1]	**Coefficient**	***p*-value**
Province		
Kampong Thom	-	-
Kandal	-0.09**	0.04
Prey Veng	-0.19***	0.000
Siem Reap	-0.09**	0.02
Svay Rieng	-0.14***	0.001
Flood proneness		
Non-flood prone	-	-
Flood-prone	-0.09***	0.001
Poverty level (IDPoor status)		
Non-IDPoor	-	-
IDPoor 1	0.1	0.4
IDPoor 2	0.1	0.3
Unknown	-0.1	0.3
Education		
No formal education	-	-
Primary schooling	0.2	0.4
Secondary schooling	0.2	0.3
University graduate	0.3	0.3
Vocational training	0.3	0.3
# times pit overflowed since ADP installed		
Never	-	-
1-3 times	0.0	0.8
4-10 times	0.0	0.9
More than 10 times	0.1	0.6
Constant	1.73***	0.000
Observations	700	
Adjusted R-Squared	0.03	

1: All coefficients of categorical variables are in reference to the first response indicated (e.g., "Non-IDPoor" and "No formal education"). Thus, all coefficients describe the difference between a given response and the reference response.

* p<0.1; ** p<0.05; *** p<0.01

Table S9. Sample Distribution

Provinces	# Districts	# Villages	# and % Households	
Kampong Thom	8	81	150	20%
Kandal	7	40	95	12%
Prey Veng	13	128	195	25%
Siem Reap	12	91	141	18%
Svay Rieng	8	112	189	25%
Total	40	452	770	100%

Table S10. Percentages of households with pierced pits by provinces and flood proneness (n = 770)

	Percentage of households
Province	
Kampong Thom	15%
Kandal	18%
Prey Veng	43%
Siem Reap	18%
Svay Rieng	62%
Flood proneness	
Non-flood prone	29%
Flood-prone	36%