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REVIEW

The ventilated improved pit latrine: a theoretical evaluation of conventional design guidelines, user adaptations and prospects for improvement

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Abstract
The ventilated improved pit latrine has the potential of meeting the sanitation needs of many households in developing countries and enhance the chances of attaining the Sustainable Development Goal (SDG) 6. However, some user adaptations of the technology appear to conflict with conventional design guidelines and may compromise the ventilation rate in the vent pipe. This would negatively affect the odour control function of the technology. This paper seeks to evaluate existing conventional design guidelines that are aimed at controlling odour and fly nuisance in the latrine to highlight their relevance and possible conflicts with existing and emerging user adaptations. It also identifies potential structural modifications that may be adopted to accommodate emerging user preferences without compromising the odour control mechanism. The review shows that, indeed, some construction practices such as provision of windows in multiple sides of the superstructure adversely affect the ventilation rate and could lead to odour problems. However, the effects of some suspected unfavourable user adaptations such as use of closed-top vent caps and ceramic seats with covers have not been investigated. Furthermore, recent studies have demonstrated the possibility of compensating for the negative effect of some user preferences with favourable environmental conditions such as high wind speed and structural modifications using a mathematical model. However, the existing model fails to account for some key design criteria and needs to be improved to make it useful for a wider application.

Keywords: Dry Sanitation, Ventilated Improved Pit, VIP Latrine, VIP Ventilation, Odour Control

Introduction

The safe collection, treatment and disposal of human excreta is a key index of the quality of life due to its direct effects on the health and productivity of the populace (Naughton and Mihelcic, 2017). According to the Joint Monitoring Programme (JMP) of the World Health Organisation (WHO) and the United Nations Children's Fund (UNICEF), safely managed sanitation services, as envisaged under Goal 6 of the Sustainable Development Goals (SDGs), can be pursued through three pathways, namely use of:

- facilities connected to a sewer system with an off-site wastewater treatment plant.
- non-sewered systems without faecal sludge treatment from which excreta is removed and transported to an off-site facility designed for faecal sludge treatment.
- non-sewered systems with in-situ treatment and disposal of excreta.

For many countries, the pursuit of safely managed sanitation services will require a multi-pathway approach. However, developing countries face significant challenges in following the first and second pathways to safely managed sanitation as listed above. This is due to municipal infrastructural limitations, especially the absence of sewerage and wastewater treatment facilities. For instance, in Sub-Saharan Africa, the coverage of sewer connections is only 8 % while that of non-sewered sanitation systems with excreta removed and treated off-site stands at 10 % (WHO/UNICEF, 2019). The situation is not different in other parts of the developing world. For example, the World Bank reported in 2013 that the percentage of wastewater collected and treated in Vietnam was 10 % while that of the Philippines and Indonesia were 4 % and 1 % respectively (World Bank, 2013). Hence, in developing countries, dry on-site sanitation technologies with in-situ treatment and disposal of excreta offer a promising pathway to safely managed sanitation services.

Even in cities where sludge treatment and disposal facilities exist, some socio-economic challenges have been reported as limiting the adoption of wet sanitation systems by some households. These challenges include low household income levels to meet the relatively higher cost of wet sanitation, unreliable water supply and lack of access to houses by cesspit emptier trucks (Hogrewe, 1993; Parkinson and Taylor, 2003; Parkinson *et al.,* 2008). This compels some households that could afford wet sanitation systems to resort to the use of dry on-site sanitation technologies with in-situ treatment and disposal of excreta. For instance, Obeng *et al.* (2015) reported instances where some households with septic tanks had converted their water-closet toilets to VIP latrines in Prampram, a coastal community in Southern Ghana, due to intermittent water supply to the community.

In Sub-Saharan Africa, the coverage of dry sanitation systems is estimated to be 31 % of the population (WHO/UNICEF, 2019). Among dry sanitation technologies, the pit latrine alone is estimated to account for 50 % of all households that have access to sanitation facilities in Sub-Saharan Africa (Nakagiri *et al.,* 2016). The popularity of pit latrines is attributed to their affordability, simplicity of operation and tolerance for a wide range of anal cleansing materials, among others (Nakagiri *et al.,* 2016). In spite of their advantages, the use of the simple pit latrine is frequently associated with the challenge of odour and fly nuisances that tend to discourage some prospective users and lead to the practice of open defecation (Cotton *et al.,* 1995; Appiah and Oduro-Kwarteng, 2011; Keraita *et al.,* 2013; Obeng *et al.,* 2015).

The need to address the challenges of odour and flies associated with the simple pit latrine led to the development of the ventilated improved pit (VIP) latrine in Zimbabwe in the

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1970s. The VIP latrine is credited with the potential of controlling these nuisances (Cotton *et al.,* 1995; Ryan and Mara, 1983a, b; Mara, 1984). These advantages, coupled with its affordability, make it a very popular choice among households in Sub-Saharan Africa and other parts of the developing world. For instance, in Lesotho, usage of the technology is reported to exceed 90 % of the population (Aiyuk and Tsepa, 2017). When built and used in accordance with recommended design and operational guidelines, the technology is said to be capable of affording its users most of the health benefits and convenience of water-borne sanitation at a relatively much lower cost (Kalbermatten *et al.,* 1980; Ryan and Mara, 1983a).

With the increasing adoption of the VIP latrine technology among urban dwellers, especially those who are constrained from using wet sanitation by some site restrictions rather than cost, various construction practices have emerged to presumably enhance the aesthetics of the technology or achieve some other user preferences. Even though no study has been found that documents the rationale behind various modifications of the VIP latrine design, they can be understood to be conscious choices made by the users to serve some preferences and interests. For instance, in Prampram, Ghana, Obeng *et al.* (2015) identified heat in latrine cubicles and entry of reptiles and rodents among barriers to latrine usage. These may inform the provision of windows in multiple sides of the superstructure to encourage circulation of air in the privy room and use of screens in windows to prevent entry of reptiles and rodents even though these practices are discouraged by conventional design guidelines.

The above observation calls for in-depth understanding of existing and emerging VIP construction practices and adaptations that are being made by latrine owners, especially those that may be at variance with conventional design and operational guidelines but are perceived to serve some user interests and preferences. Such adaptations, which may be inspired by user convenience or aesthetics, need to be assessed in terms of their possible effects on the ventilation rate through the vent pipe, which is the key performance indicator that determines the effectiveness of its odour control mechanism (Ryan and Mara, 1983a, b; Mara, 1984). Furthermore, knowledge of such user adaptations of the technology would be a crucial step towards identifying responsive or complimentary structural innovations that may allow the adaptations to be incorporated into the design of the technology without compromising its odour control mechanism. To the best of the knowledge of this author, no such thorough review has been published. Generally, technical evaluations and improvement of the VIP latrine technology, like other pit latrines, have been scarce (Nakagiri *et al.,* 2016) until recent studies were conducted by Obeng *et al.* (2019a, b, c) which have highlighted some pertinent issues with the design and application of the VIP latrine that need to be given further attention.

In response to the above gap, the objective of this paper is to review existing and emerging VIP latrine construction practices and adaptations in the light of conventional technical design and operational guidelines to assess their potential effect on the ventilation mechanism of the technology. The paper also seeks to identify potential structural interventions that may enhance the ventilation rate in the vent pipe to compensate for any negative effect of some user preferences on the ventilation rate through the vent pipe.

Approach to the Review

Literature was searched from the Scopus database in February 2021 with the keywords 'pit latrine', 'ventilated pit latrine', 'ventilated improved pit latrine' and 'VIP latrine'. Even though no time range was specified, the search identified journal publications published between 1981 and 2019. The search results were refined with the inclusion criteria 'design' and 'construction' taken successively. After reviewing the abstracts of publications that satisfied the inclusion criteria, some were found to be irrelevant and dropped from further consideration. Table 1 presents the number of journal publications identified from the literature search. In all, twelve (12) journal papers listed in Table 2 were selected based on the content of their abstracts but the full-text of two of them were inaccessible.

Table 1 Literature search criteria and results obtained

Keywords	Number of Journal Publications		
	No inclusion criterion	'Design' as inclusion criterion	'Construction' as inclusion criterion
Pit latrine	689	105	84
Ventilated pit latrine	64	16 (11[a])	8 (5[a])
Ventilated improved pit latrine	58	16 (11[a])	7 (5[a])
VIP latrine	46	15 (10[a])	7 (4[a])

[a]Number of publications found to be relevant after reviewing the abstract

The review of the scientific literature confirms the assertion of Obeng *et al.* (2019a) that *"since pioneering research in the 1970s and 1980s developed the existing VIP design guidelines, not much further work has been done to re-evaluate the relevance of these guidelines and introduce innovative modifications that would make the technology more responsive to emerging user needs and preferences"*. The above search criteria revealed fewer than five journal publications that had focused on the technical design of the VIP latrine concept. As noted in Table 2, only the works of Obeng *et al.* (2019a, b) sought to re-evaluate the design guidelines while the rest adopted the existing guidelines to evaluate construction practices. This review, therefore, had to pay attention to the old, classical journal papers published in the 1980s and 1990s since they continue to serve as the main sources of reference so far as the design and construction of the VIP latrine is concerned.

Furthermore, due to the insufficient number of peer-reviewed journal literature on the design and construction of the VIP latrine, the review involved literature from grey sources which were searched using the same keywords as stated above in the Google search engine. This led to the identification of several reports from various national and multinational institutions, published between 1980 and 2020, from which relevant design and construction guidelines as well as field practices were identified. The most salient non-journal publications that made the most significant contributions to this review are summarised in Table 3.

The focus of the review was to identify the specific guidelines that have been recommended for the efficient functioning of the VIP latrine technology with emphasis on odour and fly control and the rationale behind the guidelines. It also sought to identify existing construction practic-

Table 2 List of journal papers identified and their relevance to the review

Publication	Relevance to the review
Obeng *et al.* (2019a)	Highly relevant: sought to re-evaluate existing design guidelines
Obeng *et al.* (2019b)	Highly relevant: sought to re-evaluate existing design guidelines
Obeng et al. (2019c)	Highly relevant: adopted existing design guidelines to assess construction practices but failed to investigate reasons behind construction choices
Dumpert *et al.* (2009)	Highly relevant: adopted existing design guidelines to assess construction practices but did not seek to re-evaluate the relevance of the guidelines
Nakagiri *et al.* (2016)	Not much relevant: reviews usage and performance of pit latrines in general; provided some useful background information but not much on VIP latrine design
Marks (1993)	Not much relevant: briefly mentions the VIP latrine among types of sanitation systems used in rural and urban areas of Southern Africa
Bhagwan *et al.* (2008)	Irrelevant: discusses the merits and demerits of the VIP latrine in addressing the challenges associated with up-scaling dry sanitation technologies but does deal with the design and construction of the superstructure of the VIP latrine
Grimason *et al.* (2000)	Irrelevant: presents a survey of pit latrines and assesses respondents' willingness to upgrade to VIP latrines with a 'san-plat' (a specially designed concrete slab)
Obeng *et al.* (2016a)	Irrelevant: developed and tested a methodology for assessing the level of odour on latrines including the VIP latrine
von Munich and Mayumbelo (2007)	Irrelevant: does not address the technical aspects of the VIP latrine
Dadie-Amoah and Komba (2000)	Full-text inaccessible
Iwugo (1981)	Full-text inaccessible

es, especially those that fail to comply with guidelines and identify the field challenges or constraints that are associated with the adoption or promotion of the guidelines. Attention was also paid to identifying existing and emerging socio-economic conditions of urban and peri-urban settings of developing countries that constrain compliance to the guidelines as well as the technical interventions that may be tested and adopted to overcome any reported or foreseeable challenge.

It is noted that the review was only limited to the components of the latrine that have an influence on its odour and fly control mechanism. To this end, the review did not cover considerations for pit siting and construction. For guidelines and general information on this, the reader is directed to works such as Mara (1984), Graham and Polizzoto (2013) and Obeng *et al.* (2016b).

Overview and foundation of the VIP latrine concept

General overview of the VIP latrine concept

Generally, pit latrines consist of a cubicle built over a hole dug in the ground to receive excreta, anal cleansing material and, in some cases, sullage and refuse (Franceys *et al.,* 1992). To qualify as an improved toilet facility, as defined by the JMP

Table 3 List of non-journal publications identified and their relevance to the review

Publication	Relevance to the review
Reed (2014)	Highly relevant: A WEDC technical guide that presents the design details and operation of VIP latrines.
Mara (1984)	Highly relevant: A World Bank technical note that presents design guidelines for the VIP latrine.
Ryan and Mara (1983a)	Highly relevant: A World Bank technical note that sets out preliminary guidelines for the design of vent pipes for VIP latrines
Ryan and Mara (1983b)	Highly relevant: A World Bank technical note that suggests a methodology for field investigations into the ventilation performance of VIP latrines based on fieldwork in Botswana and Zimbabwe.
Jenkins (2020)	Relevant: It discusses the principle of stack and Bernoulli ventilation which underlies the ventilation in VIP latrines.
Autodesk (2018)	Relevant: It discusses the principle of stack and Bernoulli ventilation which underlies the ventilation in VIP latrines.
Harvey et al (2002)	Relevant: A WEDC book that describes on-site sanitation technology options in emergencies.
Franceys et al (1992)	Relevant: A WHO a guide that provides in-depth technical information about the design, construction, operation and maintenance of the major types of on-site sanitation facilities.
Kalbermatten et al (1980)	Relevant: A World Bank technical report that provides guidelines on how to design and implement appropriate water and sanitation technology projects.

under the MDGs, it is required, among other indicators, that the pit be covered with a slab (WHO/UNICEF, 2006). While the liquid component of the content of the pit seeps into the surrounding soil, the volatile constituents dissipate into the air, leaving a solid residue in the pit. Naturally, the dissipation of volatile constituents of excreta into the air generates offensive odours inside and within the vicinity of the latrine cubicle, which in turn attracts flies. The nuisances of malodour and flies are the main disadvantages of pit latrines (Franceys *et al.,* 1992).

The VIP latrine is a special type of pit latrines with an improved design intended to deal with the challenge of malodour and flies that are associated with the traditional pit latrines (Mara, 1984; Cotton *et al.,* 1995; Brikké and Bredero, 2003). Essentially, the main distinguishing feature of the VIP latrine, which is responsible for controlling odour, is the vent pipe which allows the movement of malodourous air from the pit into the atmosphere as shown in Figure 1.

Odour control is facilitated by the movement of external air at the top of the vent pipe and, also, through a window or other openings in the superstructure such as the ventilation space at the top of the door (Kalbermatten *et al.,* 1980; Ryan and Mara, 1983a, b; Mara, 1984; Cotton *et al.,* 1995; Obeng *et al.,* 2019a, b). Air that enters the pit through the squat hole displaces relatively warmer, malodorous air through the vent pipe and into the atmosphere as shown in Figure 1.

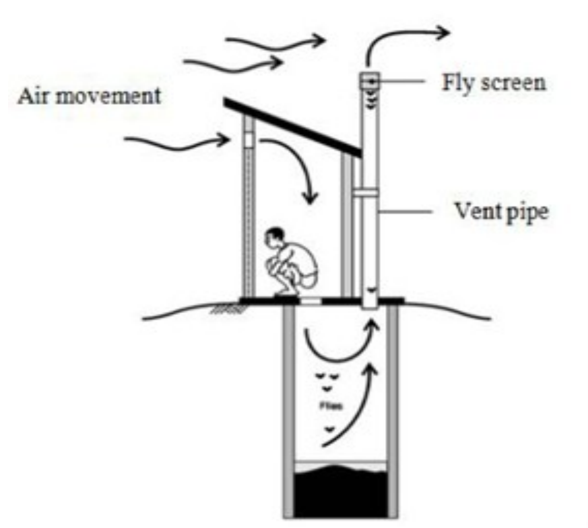


Figure 1 The ventilation mechanism in a VIP latrine (Source: Harvey *et al.,* 2002)

When built to fulfil recommended design criteria, the VIP latrine is capable of achieving odourless conditions (Ryan and Mara, 1983a; Mara, 1984). It has been established that odourless conditions are achieved when the ventilation rate in the vent pipe reaches 10 m^3/h, which is approximately six changes of the superstructure air volume per hour (Ryan and Mara, 1983a). From field studies conducted in Botswana and Zimbabwe, Ryan and Mara (1983b) recommended 20 m^3/h to guarantee adequate factor of safety, especially in urban areas where latrines may be sited very close to dwelling places. This recommended ventilation rate has been widely accepted and adopted as a guarantee for the attainment of odourless conditions in subsequent works such as Mara (1984), Dumpert *et al.* (2009), Obeng *et al.* (2016b) and Obeng *et al.* (2019a, b). This implies that, any incidence of odour in a VIP latrine in which the ventilation rate reaches 20 m^3/h could be arising from factors such as the cleanliness of the latrine rather than its structural design. Hence, the ventilation rate through the vent pipe provides a more reliable basis for assessing the potential impact of structural modifications of the design of the VIP latrine on its odour control function rather than the direct measurement of odour-producing compounds in the cubicle since the latter could be influenced by the cleanliness of the latrine.

Foundational science behind ventilation in the VIP latrine

The factors that influence the movement of malodourous air from the pit through the vent pipe are similar to those that control the movement of air in chimneys. The fundamental factor is the difference in pressure established between the ends of the vent pipe (Autodesk, 2018; Jenkins, 2020). This difference in pressure arises from two phenomena, namely the chimney or stack effect and Bernoulli's principle (Awbi, 1994; Autodesk, 2018). The chimney or stack effect results in the difference in pressure due to difference in air temperature. This occurs as cold air with a relatively higher density enters the pit and displaces warm, lighter air. This is also referred to as buoyancy-driven ventilation (Jenkins, 2020). On the other hand, Bernoulli's effect results from the action of wind at the top of the vent pipe. According to Bernoulli's principle, fast-moving air at a given height compensates for its high kinetic energy with a reduction in pressure. Hence a negative pressure is created at the top of the vent pipe, which literally sucks air from the pit, making the vent pipe act as when a straw is used to suck a drink from a bottle.

The roles of the above two phenomena in the odour removal function of the VIP latrine form the basis of various technical guidelines for the design of the superstructure and vent pipe. Each guideline is meant to enhance either the chimney or Bernoulli's effect. According to Jenkins (2020), these two phenomena are complimentary and designing for one makes the other also present. The two phenomena also explain the influence of some environmental factors, especially wind speed and ambient temperature, on the design criteria. For instance, while ambient temperature and humidity play a key role in the chimney effect, the Bernoulli's effect is critically dependent on the wind speed (Autodesk, 2018; Jenkins, 2020).

Even though most of the design guidelines, particularly those related to the superstructure, are aimed at enhancing the chimney effect, it has been proven that the Bernoulli's effect plays a much bigger role in the ventilation process. For instance, Obeng *et al.* (2019b) found that the diameter of the vent pipe, which determines the area over which the action of wind takes place, and the speed of external wind combine to account for 78% of variations in the ventilation rate through the vent pipe. This suggests that, with an appropriate size of the vent pipe and the benefit of a windy environment – or an intervention to enhance the action of wind – most of the stringent guidelines relating to the design of the superstructure could be relaxed or completely ignored. For instance, it was earlier recommended that the vent pipe should be painted black to retain heat (Kalbermatten *et al.,* 1980), but it was subsequently discovered that this is necessary only where the external wind speed is below 0.5 m/s (Mara, 1984). Notwithstanding, it would always be an advantage to have both the chimney and Bernoulli's effect operating together. For instance, when there is no wind to drive the Bernoulli's effect, the chimney effect will continue to take place if the vent pipe is being heated by the sun (Reed, 2014).

Guidelines for odour and fly nuisance control in VIP latrines

It is agreed by authors who have examined the VIP latrine design and construction concept that the technology would perform its odour and fly control function up to expectation only when a set of design and operational criteria are diligently ad-

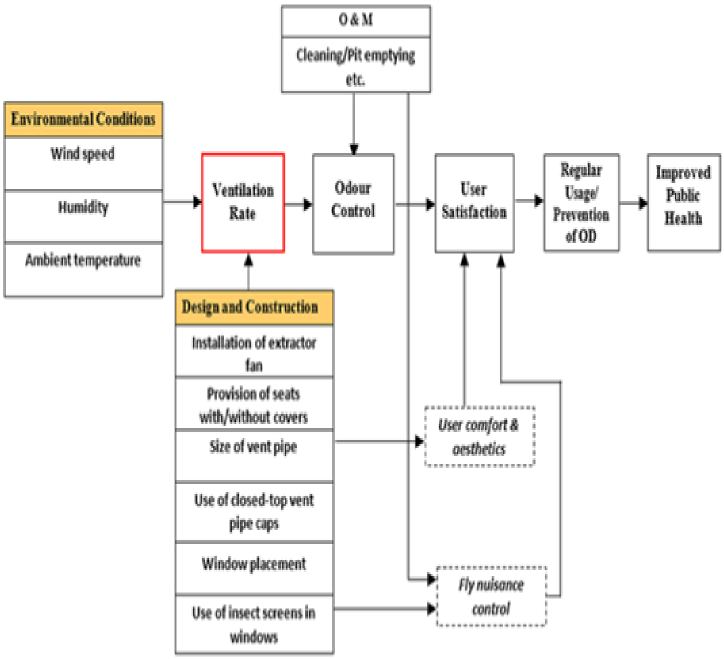


Figure 2 Conceptual framework for odour and fly control in VIP latrines

hered to (Ryan and Mara, 1983a; Mara, 1984; Obeng *et al.*, 2019a, b). Because of the need to adhere to such seemingly 'stringent' technical guidelines in order to derive optimum performance from the VIP latrine, some observers have described the technology as being complex (Jenkins and Sudgen, 2006; Reed, 2014) and difficult to construct properly (Harvey *et al.*, 2002). To guide field practitioners and potential users in their adoption and usage of the technology, several technical notes, handbooks and user guides abound, mostly from grey literature sources, that discuss these design and operational criteria that are to be followed in the construction and usage of the latrine.

As shown in Figure 2, existing body of literature reveals that odour and fly control in the latrine technology are critically dependent on design and construction criteria including:

i. design and positioning of the vent pipe
ii. design and orientation of the superstructure (including placement of windows)
iii. design of the user interface (squat hole/pedestal with or without a cover)

Technical decisions on the above design and construction criteria combine with environmental factors to determine the ventilation rate through the vent pipe as demonstrated by Mara (19834) and Obeng *et al.* (2019b). In turn, the ventilation rate also combines with operation and maintenance practices to determine the effectiveness of odour and fly nuisance control, which are major determinants of user satisfaction (Obeng *et al.*, 2019c). User satisfaction is also influenced by the aesthetics and comfort the user derives from the latrine design and construction (Obeng *et al.*, 2015). Salient technical guidelines for the design and construction of the VIP latrine in relation to the prevailing environmental conditions are reviewed in the following sub-sections of this paper. As mentioned earlier, operation and maintenance guidelines are not covered in this review.

Design and positioning of the vent pipe

The vent pipe is the main feature of the VIP latrine that distinguishes it from the traditional pit latrine (Ryan and Mara, 1983a; Franceys *et al.*, 1992; Harvey *et al.*, 2002). It serves two purposes that are crucial in overcoming the weaknesses of the traditional pit latrine (Franceys *et al.*, 1992; Brikké and Bredero, 2003):

- It helps to create a draught of air from the superstructure via the squat hole into the pit and up the vent pipe. This is responsible for the removal of malodourous air from the pit to keep the superstructure free from malodour.
- It directs flies produced in the pit to the bright light of the sky which is visible to flies from the pit. The flies are prevented from exiting the vent pipe by a screen that is fixed at its top and die of dehydration or fall back into the pit after several unsuccessful attempts.

Depending on local availability and the budget of the prospective toilet owner, various materials are used for the construction of vent pipes. These include asbestos cement (AC), polyvinyl chloride (PVC), unplasticized PVC (uPVC), bricks, blockwork and cement-rendered reeds (Ryan and Mara, 1983a; Reed, 2014). For urban centres, the most popular material used for vent pipes is PVC. PVC and asbestos pipes may be more expensive, but they offer a smoother surface for the passage of air and, hence, minimise head losses in the vent pipe as compared to brickwork, bamboo and cement-rendered reeds. Generally, the smoother the surface of the pipe material, the smaller the size required as seen in Table 4. In Cape Coast, Ghana, Obeng *et al.* (2019c) found all VIP latrines to be fitted with PVC vent pipes. In constructing the vent pipe, the most important design criteria for which guidelines have been developed are:

- the diameter of the vent pipe
- the height relative to the latrine roof
- fixing a screen at the top of the vent pipe
- the positioning of the vent pipe

Vent pipe diameter

Obeng *et al.* (2019b) reported that the diameter of the vent pipe is the design parameter with the greatest influence on the ventilation rate. This is attributed to the fact that the diameter of the vent pipe determines the area over which the suction effect of wind operates to create the updraught of air from the pit (Ryan and Mara, 1983a). The recommended size of vent pipes depends on the material used for the vent pipe and the desired ventilation rate to be achieved. Generally, materials that have rough surfaces require bigger sizes of vent pipes (Franceys *et al.*, 1992) apparently due to the resistance to air flow over the rough surface. For the commonest materials used for vent pipes, the recommended sizes to achieve the minimum and recommended ventilation rates of 10 m^3/h and 20 m^3/h respectively are summarised in Table 4. It should, however, be noted that, for multiple-pit latrines, Ryan and Mara (1983a) recommend increasing the dimensions of PVC pipes to 200 mm to provide adequate ventilation for pits serving two cubicles.

As one key component that makes the VIP latrine more expensive than the traditional pit latrine, the size of the vent pipe has been reported to be compromised as a cost-cutting measure. For instance, in the case of PVC, the recommended size of 150 mm is scarcely used in Ghana. Obeng *et al.* (2019c) reported only 100 mm pipes were found in a survey in Cape Coast even though the average wind speed (2.7 m/s) was found to be less than 3 m/s. The authors suggested that this universal noncompliance to the recommended diameter may be attributed to economic factors. First, the cost of the 150 mm pipe was found to be 300% of that of the 100 mm pipe, with the actual difference in cost (US$10.66) being 5.4 times Ghana's daily minimum wage at the time. In Northern Ghana, where income levels are relatively even lower, Dumpert (2008) found the cost of the 100 mm vent pipe to be equivalent to 11 times of the average person's daily earning. This suggests that the 150 mm vent pipe would cost the average person more than

Table 4 Recommended sizes of vent pipes of different materials

Type of material used for vent pipe	Size required for Minimum ventilation rate of 10 m^3/h	Size required for Recommended ventilation rate of 20 m^3/h
Cement-rendered, bamboo or other rural vent pipes	200 mm diameter	230 mm diameter
Brickwork	180 mm square	230 mm square
Asbestos cement (AC) or polyvinyl chloride (PVC) pipe	100 mm diameter	150 mm diameter[a]

[a]May be reduced to 100 mm where the local wind speed exceeds 3 m/s.
Sources: Ryan and Mara (1983a); Mara (1984); Franceys *et al.* (1992); Reed (2014); Obeng *et al.* (2016b)

a whole month's earning. Secondly, Obeng *et al.* (2019c) found that the 150 mm pipe was scarce on the local market, apparently due to low patronage. Aside these economic factors, noncompliance to the recommended diameter may result from ignorance of the technical guidelines on the part of artisans and latrine owners. It could also arise from the design of capacity building programmes and other intervention packages by non-governmental organisations (NGOs) and government agencies.

Based on their experience in Cape Coast, Obeng *et al.* (2019c) recommended further research to explore opportunities for enhancing the ventilation rate with 100 mm PVC vent pipes. Among potential interventions, they recommended the testing of the effect of an air extractor fan, shown in Figure 3a, used on a 100 mm pipe to assess its impact on the ventilation rate. The prospect of this intervention is inspired by the use of such fans in the enviro loo toilet (Enviro Loo, 2013). It is also supported by the fact that the action of wind on top of the vent pipe is the second most important factor that affects the ventilation rate in the VIP latrine's vent pipe (aside the diameter) and accounts for 25 % of changes in the ventilation rate (Obeng *et al.,* 2019b). However, any investigation to assess their usefulness in enhancing the ventilation rate in the VIP latrine should include their effect on other requirements of the proper functioning of the VIP latrine concept, notably the exposure of the top of the vent pipe to sunlight to control flies. It should also include an assessment of how it affects the placement of an insect screen to prevent escape of flies from the pit.

(a) Air extractor fan

(b) Air extractor fan used in an enviro loo toilet

Figure 3 Air extractor fan and its application in the enviro loo toilet

Height of vent pipe

The significance of the height of the vent pipe in the design of the VIP latrine derives from the need to ensure free movement of air at the top of the pipe (Mara, 1984; Franceys *et al.,* 1992). Thus, the essence of a minimum vent pipe height is "to achieve satisfactory air movement" at the top of the pipe (Franceys *et al.,* 1992). It is generally recommended that the height of the vent pipe should be at least 500 mm from the highest point of the roof in the case of slanted roofs but up to the highest point (apex) when a conical roof is used (Ryan and Mara, 1983a; Mara, 1984, Franceys *et al.,* 1992; Reed, 2014).

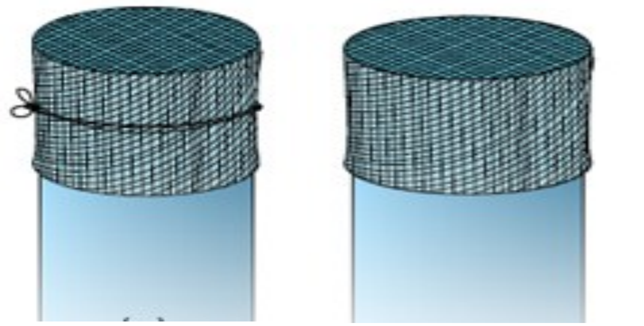
However, in their recent work to examine the relative contribution of various design criteria towards the ventilation rate in the vent pipe, Obeng *et al.* (2019b) concluded that, the most important consideration is to ensure that the top of the vent pipe is free from obstruction. This is because their field investigations revealed that varying the height of the vent pipe between 250 and 1000 mm above the highest point of the roof made no significant difference in the ventilation rate through the vent pipe. It must, however, be noted that the minimum height they tested (250 mm) was free from obstruction. Therefore, prospective builders or owners who seek to use a vent pipe height of 250 mm based on this study must ensure that the top is free from obstruction. It should also be noted that the study only focused on the ventilation rate through the vent pipe but did not assess the effect of the height of the vent pipe on the dispersal of odour in the immediate environment, which is also a key consideration in the determination of the height of the vent pipe. In the opinion of this paper, the existing guideline of 500 mm should be adhered to, as much as possible, even though Aiyuk and Tsepa (2017) assert that, an effective height of 300 mm above the roof is enough to avoid recirculation of odorous gases into the latrine cubicle.

Fixing a screen at the top of the vent pipe

Fixing a fly screen on the top of the vent pipe is a key requirement for the fly control function of the VIP latrine (Harvey *et al.,* 2002; Reed, 2014) and the broader requirement for a sanitation technology to serve as a barrier to disease transmission. If omitted, flies from the latrine pit would freely escape to the immediate households with pathogenic organism which may be passed on to a new host through uncovered food (Mara *et al.,* 2010). In selecting a screen, the key requirement is that it should be fly- and mosquito-proof (Ryan and Mara, 1983a; Mara, 1984; Harvey *et al.,* 2002). To be specific, Ryan and Mara (1983a) and Mara (1984) recommend apertures no greater than 1.2 mm x 1.5 mm even though Dumpert (2008) observed that the use of screens with 2 mm x 2 mm apertures in Northern Ghana served the purpose appropriately. Another consideration is the material used for the screen, which should be corrosion-resistant since it must withstand adverse conditions such as sunlight, high temperatures and potentially corrosive gases from the pit (Ryan and Mara, 1983a; Mara, 1984).

A concern that is frequently expressed about the fixing of the fly screen is its tendency to reduce the ventilation rate due to head loss across the screen. Among 30 VIP latrines studied in Northern Ghana, Dumpert (2008) recorded the highest ventilation rate in one of two of the latrines that had no fly screens. This may account for why the majority of vent pipes in a study conducted in Lesotho (Aiyuk and Tsepa, 2017) had no fly screens and could pose health risks to the residents living within the vicinity of the latrines. Recommendations for minimising this effect of fly screens include belling (enlarging) the top end of the vent pipe to compensate in part for the head loss (Ryan and Mara, 1983a; Franceys *et al.,* 1992) and avoiding screens with apertures smaller than 1.2 mm x 1.5 mm (Ryan and Mara, 1983a; Reed, 2014). Nevertheless, bigger apertures such as the 5 mm x 5 mm reportedly used in Lesotho (Aiyuk and Tsepa, 2017) would allow flies and mosquitos to sneak through and would not serve the intended purpose.

The actual fixing of the screen may be done by tying it to the vent pipe with a string or glued to the vent pipe as shown in Figure 4. Before tying the net to the vent pipe, it is recommended to file the edge of the pipe to smoothen it so that it does not damage the net (Ryan and Mara, 1983a).



(a) Screen tied by a string (b) Screen glued to vent pipe

Figure 4 Options of fixing a screen on a vent pipe (Source: Adapted from Reed, 2014)

Probably, as a measure to provide protection to the net from perching birds or minimise ingression of rainwater, some vent pipes are fitted with various types of vent caps such as those shown in Figure 5. This is a demonstration of a lack of understanding of the VIP latrine design concept (Dumpert, 2008) since the practice can interfere with the suction effect of wind and, hence, the updraught of air through the vent pipe. It is, therefore, discouraged by Ryan and Mara (1983a). This practice is particularly common in Ghana where the vent caps shown in Figure 5 were photographed. The owner of the latrine whose vent piped was capped as shown in Figure 5b stated that his motivation was to prevent the ingression of rainwater into the pit and, also, to prevent the immediate environment from smelling (Dumpert, 2008). It would be interesting to investigate the extent to which the use of the industrially prefabricated closed-top vent caps affects the ventilation rate in the vent pipe and what alternative measures may be adopted to shield the fly screen from damage.

(a) Industrially prefabricated (b) Home-made Dumpert, 2008

Figure 5 VIP latrine vent caps used in Ghana

Positioning of the vent pipe

The vent pipe is expected to be positioned in a location that allows free flow of air over the top. To this end, it is recommended to be positioned at the windward side of the superstructure just as doors and windows. However, where its location at the windward side would interfere with the placement of doors or windows, the latter should be given preference at the windward side (Ryan and Mara, 1983b; Mara, 1984). To keep it free from obstructions, it is generally recommended to site the latrine at least 2 m away from overhanging branches or other obstructions (Mara, 1984)

The vent pipe should be installed in such a way that it is, as much as possible, straight and vertical (Ryan and Mara, 1983a; Mara, 1984; Franceys *et al.,* 1992). This guideline is meant to ensure that as much light as possible is thrown down the pipe into the pit to attract flies towards the top of the pipe rather than the latrine cubicle. According to the World Bank (2002), initial experiments in Zimbabwe reported by Morgan (1977) indicated that, the installation of a vent pipe led to the observation of an average of only 2 flies per day in the cubicle of the latrine as compared to 179 in a corresponding simple pit latrine without a vent pipe that was monitored simultaneously. Over a 78-day monitoring period, the actual number of flies counted in the vented pit latrines was 146 as compared to 13,953 in the simple pit latrine.

A straight vent pipe also enhances the air movement since bends would introduce energy losses in the movement of air (Franceys *et al.,* 1992). To keep the vent pipe straight in its position, it should be firmly attached to the cover slab and the superstructure as shown in Figure 6. In the cover slab, the base should sit on a socket as shown in Figure 6a in order to prevent the pipe from slipping down into the pit. Furthermore, steel straps or a galvanised steel wire should be used to attach the pipe firmly to the superstructure as shown in Figure 6b and also earlier in Figure 1.

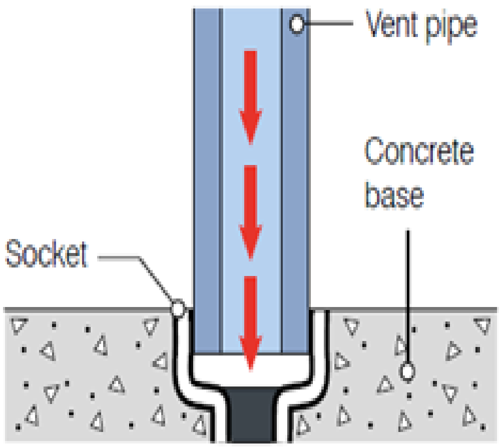
Superstructure design and orientation

Among guidelines that have been recommended for the design of the VIP latrine superstructure are the following salient ones (Ryan and Mara, 1983a; Mara, 1984; Reed, 2014):

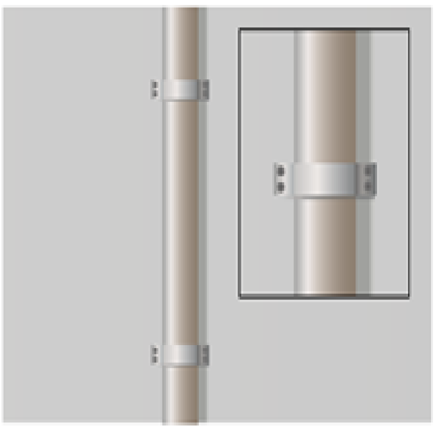
- the latrine should be oriented toward the windward direction, i.e., the door and/or window should be positioned in the side facing the direction from which the local wind blows, with none provided in other sides of the superstructure.
- use of insect screens in windows should be avoided.
- the latrine cubicle should be kept dark.

Orientation/placement of doors and windows

This is, perhaps, the most important factor that influences the odour removal function of the latrine as far as the design of the superstructure is concerned. It is highly recommended that doors and windows (if any) are provided in the windward direction (i.e., facing the direction from which the wind blows) and that no additional windows or openings are provided in other sides of the superstructure (Ryan and Mara, 1983a; Mara, 1984). Positioning doors and windows in the windward direction allows direct entry of air into the cubicle as shown in Figure 1. On the other hand, providing windows in other sides of the superstructure leads to 'escape' or short circuiting of the wind which would otherwise increase the pressure in the cubicle. High pressure in the cubicle is required to push air down the drop hole to flush out warm, malodourous air from the pit through the vent pipe (Mara, 1984).



(a) Fixing the vent pipe into the cover slab



(b) Attaching the vent pipe to the superstructure

Figure 6 Fixing the vent pipe firmly to the cover slab and superstructure (Source: Reed, 2014)

Even though it has been proven to be a very important design criterion, the requirement of having VIP latrines oriented toward the windward side is not as simple as it appears. This is, especially, so because of the informal construction processes that most households in low-income settings adopt in the construction of their toilets. Firstly, households and local artisans are faced with the challenge of being able to establish the most effective windward direction just by their sense of intuition without any scientific equipment. Secondly, given the rapid uncontrolled physical development in low-income settings, especially extensions to existing houses (Hogrewe *et al.,* 1993; Parkinson and Taylor, 2003; Paterson *et al.,* 2007), the local wind direction may change after a well oriented latrine has been constructed and render it disoriented (Obeng *et al.,* 2015). In Northern Ghana, for instance, Dumpert *et al.* (2009) found that only 36 % of VIP latrines had their main air entry point oriented or partially oriented towards the windward direction. The remaining latrines had their air entry points being more than 60^{o} deviated from the direction of the prevailing wind at the time of measurement.

Regarding the avoidance of windows in other sides of the superstructure aside the windward direction, a study in Cape Coast (Obeng *et al.,* 2019c) revealed that 31 % of latrines sampled had windows in multiple sides of the superstructure. In the case of Northern Ghana, Dumpert *et al.* (2009) found the proportion to be 50 %, with 20 % of the total sample having the additional window located at the opposite side to that of the main window or opening. Even though the rationale behind the provision of windows in multiple sides of the superstructure has not been established, Obeng *et al.* (2015) alluded to the citing of heat in latrines as a barrier to regular usage in Prampram, Ghana, as a possible motivation that makes some latrine owners to do that to, ostensibly, enhance air circulation in the privy room.

Based on field trials in Ghana, Obeng *et al.* (2019a) have suggested that in built-up low-income areas, it may be a good idea to provide windows in multiple sides of the superstructure rather than risk having a latrine with window(s) provided in a single side that may turn up not to be the windward side. In their study involving an experimental latrine fitted with a 150 mm vent pipe, the average ventilation rate decreased from 74 m^3/h in the standard superstructure (having a window only in the windward side) to 48 m^3/h in a setup having windows in all sides. However, when a window was provided only in a side that was not the windward side, the ventilation rate in the disoriented latrine was found to decrease to 25 m^3/h, which is quite close to the recommended threshold of 20 m^3/h. Considering the fact that most households use 100 mm vent pipes in Ghana rather than the recommended 150 mm, it is anticipated that a latrine with windows in a single side that is disoriented may not have a good chance to attain the recommended 20 m^3/h ventilation rate as compared to one with windows in multiple sides. This assertion is supported by the observation of Dumpert (2008) in Northern Ghana where latrines with windows in multiple sides of the superstructure recorded a cumulative ventilation rate that was significantly higher (24 % higher, $p=0.01$) than those having windows in only one side. Additional openings may have improved the ventilation because most of the latrines studied by Dumpert (64 %) were, actually, disoriented from the windward direction. Nevertheless, further studies are required to investigate the effect of such superstructure modifications on the ventilation rate and the potential effect on fly control due to a possible admission of more light into the latrine cubicle.

Use of insect screens

The use of insect screens in windows is said to cause a reduction in air pressure in the privy room due to head losses across the screens and, therefore, not recommended (Mara, 1984). As compared to an identical latrine without screens in the windows, Obeng *et al.* (2019b) found that the installation of screens in the windows could lead to 7 % reduction in the ventilation rate through the vent pipe if all other factors are held constant. However, Obeng *et al.* (2019a) observed that the effect of this design criterion could be overlooked by using the recommended 150 mm vent pipe. In an experimental latrine fitted with a 150 mm vent pipe and without a screen in its window, they recorded an average ventilation rate of 74 m^3/h but when an insect screen was installed in its window, the ventilation rate dropped to 60 m^3/h, which is still 3 times the recommended rate of 20 m^3/h. Nevertheless, when a 100 mm vent pipe was used, as commonly found in Ghana, the ventilation rate dropped to as low as 18 m^3/h. Thus, a combination of the use of insect screens with provision of windows in multiple windows when a 100 mm vent pipe is used could cause odour problems.

The likelihood of having odour problems when insect screens are installed in windows of latrines fitted with 100 mm vent pipes calls for attention due to the popularity of these design options. In Cape Coast Ghana, Obeng *et al.* (2019c) found all private VIP latrines they sampled to be fitted with 100 mm vent pipes and 87 % of them had insect screens in their windows. Their study did not investigate the rationale for the use of insect screens in windows. However, this practice has been proposed as a potential solution to the entry of reptiles and rodents into the latrine cubicle, which has been identified as a barrier to regular usage (Obeng *et al.,* 2015). With the constraints surrounding the use of 150 mm vent pipes, there is the need for further research to identify other innovative options for enhancing the ventilation rate in latrines fitted with 100 mm vent pipes to allow the use of insect screens in windows even when windows are provided in multiple sides of the superstructure.

Keeping the latrine cubicle dark

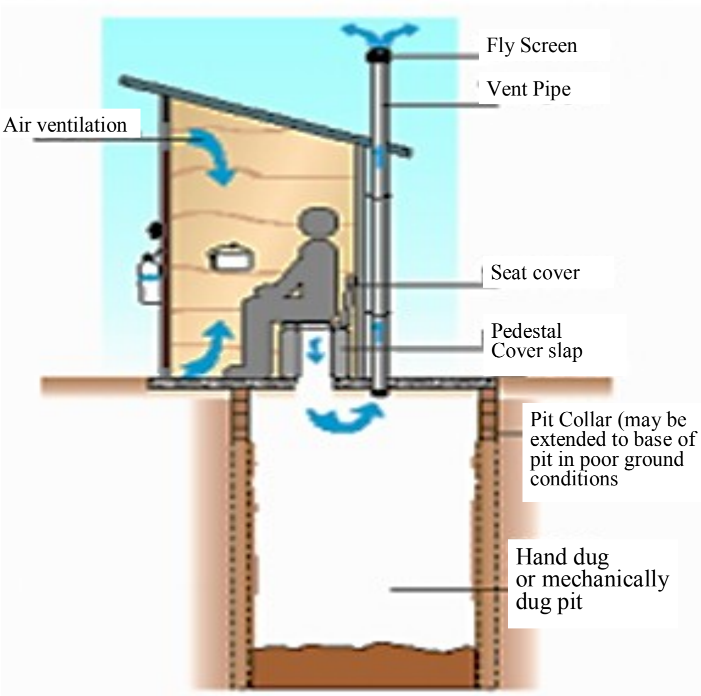
The latrine cubicle is advised to be kept dark as a measure against attraction of flies from the pit into the cubicle instead of the top of the vent pipe (Mara, 1984; Marks, 1993; Harvey *et al.,* 2002; Reed, 2014). A study in Botswana and Tanzania found that 90% of flies from the pit of a VIP latrine were attracted to the top of the vent pipe when the door of the latrine was closed to keep the inside dark as compared to 50% when the door was left open (Curtis and Hawkins, 1982). However, this requirement, coupled with the entry of rodents and reptiles, is a major barrier to the use of the VIP latrine by children, in particular (Reed, 2014; Obeng *et al.,* 2015). Even though placement of insect traps over the drop hole has been used to trap mosquitoes in Tanzania and Botswana (Curtis, 1981; Curtis and Hawkins, 1982) its application for trapping flies from the pit may be explored in latrines as a complimentary measure when a well-lighted cubicle is desired.

The use of the multi-window design may conflict with the requirement of keeping the cubicle dark and needs to be investigated. So far, the advantage of the multi-window design has only been assessed in relation to the ventilation rate but not fly control. Nevertheless, the effect of an additional 'small' window in another side of the superstructure may not be as high as opening the door of the latrine as in the case of Curtis and Hawkins (1982).

Latrine user interface (squat hole/pedestal) design and construction

The conventional design of the VIP latrines allows the provision of an ordinary squat hole as shown in Figure 1 or a pedestal (or seat) on which the user may sit as shown in Figure 7. No study has been found that investigates how the provision of a seat affects the movement of air into the pit and, hence, the ventilation rate through the vent pipe. Whichever option is adopted, it is expected to be left uncovered when the latrine is not in use in order to allow continuous movement of air into the pit to displace malodourous air through the vent pipe (Mara, 1984; Reed, 2014).

Some users prefer to squat instead of sitting due to fear of contracting infectious diseases as observed in Prampram where



(a) Schematic diagram of a VIP latrine with a pedestal

(b) a prefabricated ceramic seat

Figure 7 VIP latrine with a pedestal (Source: Moilwa, 2006) use of latrines is perceived to be associated with transmission of candidiasis (Obeng, 2016c). However, for household latrines, the use of a pedestal on which the user may sit may be attractive, especially to children and the aged. In Prampram, having to squat to defecate was identified as one of the barriers to latrine usage (Obeng *et al.,* 2015).

For users in urban centres for whom cost is not a major constraint, various construction practices have emerged to enhance the aesthetics of the technology or achieve some other goals. Among these is the use of prefabricated ceramic seats with covers as shown in Figure 7b. In Northern Ghana, Dumpert (2008) found 90 % of VIP latrines having their drop holes covered. As explained above, the use of such seat covers will prevent movement of air into the pit to maintain the odour control function of the latrine. In the case of Northern Ghana, Dumpert (2008) found the ventilation rate in latrines that did not have covers on the drop hole to be 24 % higher (p=0.09).

However, to minimise this effect, industrial prefabrication of the covers may involve partially lining them with insect screens to allow passage of air while restraining insects from leaving the pit. This would be technically similar to the use of mosquito traps in Tanzania and Botswana as cited earlier (Curtis, 1981; Curtis and Hawkins, 1982). While head losses across a screen placed over VIP latrine drop hole is recognised as negatively affecting the ventilation rate (Ryan and Mara, 1983a; Mara, 1984), the magnitude of the effect has not been established. It would be particularly of interest to examine whether the effect of a modified seat cover, which is partially lined with an insect screen, could achieve the recommended ventilation rate. Similarly, it would be of interest to investigate whether the effect of a full or partially-screened seat cover could be compensated for by the use of an air extractor fan on a 100 mm or 150 mm vent pipe.

Determinants of the ventilation rate in a VIP latrine

The effects of various environmental factors and design criteria on the ventilation rate in the VIP vent pipe have been quite well documented. However, the relative magnitude of the effect of the various factors has only recently been investigated by Obeng *et al.* (2019b) and led to the model shown in Equation 1

$$lnQ = 0.226 + 0.012D + 0.287Vwind - 0.323SPT + 0.010Hum - 0.068SRC + 0.028Temp \quad (1)$$

where:

Q is the ventilation rate in the vent pipe measured at the mid-point (m^3/h)

D is the diameter of the vent pipe (mm)

Vwind is the external wind speed measured at the top of the vent pipe (m/s)

SPT is a categorical variable for window positioning in superstructure: 0 if standard (i.e., window provided only in the windward side); 1 if windows provided in multiple sides; 0 was the reference category.

Hum is relative humidity (%)

SCR is a categorical variable for provision/absence of an insect screen in window(s): 0 if no screens are provided; 1 if screens are provided; 0 was the reference category.

Temp is external or ambient air temperature (^oC)

Such a mathematical model that establishes the determinants of the ventilation rate is needed to predict variations in the rate under changing environmental conditions and a combination of design criteria. This would provide an insight into how advantage can be taken of one design criterion or a favourable environmental factor to purposively ‘violate’ some other guideline in order to satisfy some user preferences. For instance, the model developed by Obeng *et al.* (2019b) suggests that increasing the diameter of the vent pipe by 1 mm leads to 1.2% increase in the ventilation rate. In other words, replacing the 100 mm vent pipe commonly used in Ghana with the recommended 150 mm size leads to 60 % increase in the ventilation rate. On the other hand, providing windows in multiple sides of the superstructure leads to 32 % reduction in the ventilation rate while use of insect screens in the windows leads to 7 % reduction. This implies that if a prospective user prefers to allow entry of air in multiple sides of the superstructure to enhance air circulation in the cubicle as well as restraining the entry of rodents and reptiles with the use of insect screens in the windows, then the combined negative effect of these design preferences may be compensated for by using a 150 mm vent pipe instead of 100 mm provided cost is not a limiting factor.

Even though the model developed by Obeng *et al.* (2019b) is useful, it has limitations that need to be improved upon to allow a broader application. Notably, their model did not account for the effect of some common construction practices such as the provision of a seat with or without a cover and use of closed-top caps on vent pipes. Hence, it would be useful to have an improved model that accounts for these existing design practices as well as the potential effect of possible improvements such as use of full or partially-screened seat covers and an air extractor unit on the vent pipe.

Conclusions

The VIP latrine has the potential of meeting the sanitation needs of many rural and urban dwellers who are constrained by some technical or socio-economic factors from accessing other technologies that are higher up on the sanitation ladder. It offers low-income countries a more realistic pathway to safely-managed sanitation as envisaged under the SDG 6. However, the technical design and construction of the VIP latrine has not been given much attention by the scientific community since pioneering research work in the last quarter of the 20th Century led to the development of the conventional guidelines that are currently widely applied by researchers and field practitioners.

Apart from a few (less than five) peer-reviewed journal papers that have sought to question or re-evaluate the relevance of some of the existing guidelines to emerging user preferences and demand for aesthetics among urban dwellers, nearly all available literature adopt and apply the classical guidelines as they are. Nevertheless, reported barriers to latrine usage (such as heat and darkness in the cubicle, entry of rodents and reptiles into the latrine cubicle), the high cost of the recommended size of vent pipe, as well as user demand for an aesthetically pleasing user interface are leading to construction practices that are not consistent with the existing technical guidelines. Some of these practices, such as provision of windows in multiple sides of the superstructure and installation of insect screens in windows, have recently been proven to adversely affect the ventilation rate but others, such as use of closed-top vent caps and ceramic seats with covers have not been investigated. Embracing user preferences that undermine the attainment of the recommended ventilation rate without a complimentary structural intervention to enhance the chimney or Bernoulli’s effect would lead to odour generation which could eventually lead to abandonment and the practice of open defection. Hence, there is the need to reengineer the VIP latrine concept with technical modifications that would accommodate such emerging user preferences without compromising the ability of the technology to achieve the recommended ventilation rate. Furthermore, more recent studies have demonstrated the possibility of taking advantage of some favourable environmental conditions or design criteria to compensate for the negative effect of some user preferences. It is, therefore, necessary to have a robust mathematical model that could reliably predict the ventilation rate given a set of environmental and structural variables. Such a model should, as much as possible, account for as many existing and emerging construction practices as possible.

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Conflict of Interest Declaration
The authors disclose no potential conflict of interest.

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