GLOBAL WATER PATHOGEN PROJECT

PART FOUR. MANAGEMENT OF RISK FROM EXCRETA AND WASTEWATER

COMPOSTING AND DRY DESICCATING TOILETS (LATRINES)

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Summary

Composting and dry desiccating toilets (also referred to as latrines) are popular onsite sanitation technologies where the contents (i.e., excreta) can be reused and returned to the local environment within the sanitation chain. A *composting toilet* is designed and operated to enhance conditions within the waste pile of human excreta to promote aerobic biological processes that gives off heat, which in turn can inactivate pathogens. A *dry desiccating toilet* is designed and operated to enhance the physical process of desiccation (or drying) of the waste pile that contains human excreta, which in turn can inactivate pathogens. Due to space constraints, urine diversion is not a focus of this chapter.

Some of the primary design and operational parameters that influence pathogen inactivation in both technologies are: (1) appropriate chamber size for adequate *storage time* given the number of users and expected *temperature* and *moisture content* in the pile of excrement, (2) inclusion of designs or materials that increase temperature and decrease moisture content, (3) whether urine is diverted from the feces, (4) type and amount of dry bulking material (i.e., desiccant) added that influences the porosity, moisture content, pH, and C/N ratio of the excreta, and (5) presence or addition of free ammonia.

Most composting and dry desiccating toilets have a vault volume of at least 1 m³ and most likely a volume greater than that. Some desiccating toilets are designed to have a storage time as low as 60 days for situations where design modifications are made to enhance temperature; however, a minimum 18 month storage time is now recommended in most situations for both types of toilets.

Any increase in chamber temperature that is transferred to the pile of excreta will enhance pathogen inactivation in both composting and dry desiccation toilets. Pathogens can be destroyed at ambient temperature with sufficient contact (storage) times. For the most resistant pathogens temperatures greater than $\approx 45^{\circ}\text{C}$ would need to be maintained for many months.

Temperature can be enhanced in both types of toilets by design additions by insulating chambers to reduce conductive heat lost and external heating through addition of solar panels. Several operational factors influence temperature of the excreta in a composting toilet: (1) aeration (controlled by mixing and the porosity of the pile), (2) partial desiccation to reduce the moisture content of the pile but not so much that it kills off the microorganisms that are degrading the organic carbon, and, (3) an optimum

carbon-to-nitrogen (C/N) ratio. The C/N ratio is not an important parameter in the operation of a dry desiccating toilet. However, it is important for proper operation of a composting toilet. This is because feces have a C/N ratio of 6-10 (dry mass basis); however, the composting process is most effective at achieving an increased temperature in the pile of excreta when the C/N ratio is raised to 20:1 to 30:1

The type of dry material and the amount added to a composting or desiccating toilet after each use has a large impact on pathogen destruction and whether the toilet performs as a dry desiccation or composting toilet. Common desiccants that reduce moisture and/or raise pH are ash (from burning wood or other materials), sawdust, dry soil or sand, dry leaves and grass, burnt rice husks, lime (quicklime or hydrated lime), crushed oyster shells, and shea nut shells. Selection of a desiccant is typically determined by what is locally and seasonally available and is cost effective. Desiccant selection should also be carefully linked to the toilet operation and primary environmental factors and mechanisms that lead to pathogen destruction. This is because some desiccants absorb moisture well, some are good sources of carbon, and some will increase the mixture's pH. And for operation of a composting toilet, a bulky desiccant will support aeration in the chamber's contents through increasing the porosity of the pile.

Inactivation is also promoted by another key factor of increasing pH with addition of bulking materials such as lime and specific types of ash. Achieving a pH of > 12 is a well-established method to inactivate pathogens in sludge. The presence or addition of free ammonia can also be employed to reduce pathogen concentrations.

For dry desiccating toilets, significant log removal is expected. At high pH, low moisture content, and a storage time of 6-12 months with addition of wood ash or lime, one can achieve up to a 6 log₁₀ reduction of bacteria, 4 log₁₀ reduction in viruses, and complete removal of protozoa and helminths (Stenström et al., 2011). It is expected that that a storage time of 1.5 to 2 years will completely remove remaining bacteria and viruses (Stenström et al., 2011).

In a composting toilet, all pathogens are expected to be removed if thermophilic temperatures ($>40^{\circ}\text{C}$) are achieved and a contact time of at least 1.5 years is provided. However, this elevated temperature may be difficult to obtain in the field without consideration of how design and operation impact the composting process and resulting pathogen removal.

1.0 Brief Technology Description

Composting and dry desiccating toilets (also referred to as latrines) are popular onsite sanitation technologies where the contents (i.e., excreta) can be reused and returned to the local environment within the sanitation chain (see Figure 1). A composting toilet is designed and operated to enhance conditions within the waste pile of human excreta to promote aerobic biological processes

that gives off heat, which in turn can inactivate pathogens. A dry desiccating toilet is designed and operated to enhance the physical process of desiccation (or drying) of the waste pile that contains human excreta, which in turn can inactivate pathogens. This chapter focuses solely on operating these two sanitation technologies as batch systems.

Figure 1. Location of composting and dry desiccating toilets (latrines) in the overall sanitation chain (adapted from the "Sanitation Value Chain" by SuSanA Secretariat, licensed under CC BY 2.0)

More information about design and operation considerations for composting and dry desiccating toilets is available; for example, Schönning and Stenström (2004), Mihelcic et al. (2009), Berger (2011), and Tilley et al. (2014). There are also extensive resources available at the Sustainable Sanitation Alliance Library (<https://www.susana.org/en/knowledge-hub/resources-and-publications/library>). A recent journal article evaluated how use of technologies discussed in this chapter and other demographic characteristics influences users' perceptions of excreta for optimum resource recovery (Naughton et al., 2018).

Composting and dry desiccating toilets are found throughout developing and developed countries, mostly in rural areas, but sometimes in urban and peri-urban settlements. Composting toilets are also often installed in eco-resorts, vacation homes, marinas, and environmentally certified buildings (Cordova and Knuth, 2005). The desiccating and composting toilet can meet the necessary

requirements for the suitable deposition of excreta by the user and the environmental conditions to promote the drying, storage and/or composting of the excreta, aiming at their safe reuse in agriculture.

Drying (measured as moisture content), temperature, and the length of storage (i.e., contact or residence time) are key operating parameters that impact pathogen inactivation. Inactivation is also promoted by another key factor of increasing pH with addition of bulking materials such as lime and specific types of ash. The presence or addition of free ammonia can also be employed to reduce pathogen concentrations (Pescon et al., 2007; Mehl et al., 2011; Trimmer et al., 2016).

A schematic example of a double vault ventilated improved composting toilet with urine diversion is shown in Figure 2. Figure 3 provides examples of what these types of toilets look like in the field. The composting process is characterised by the biological conversion of excreta into an aesthetically acceptable product.

Figure 2. Examples of double vault composting toilets only one vault is in use at any given time, while excreta is composted in the other, the left side shows a false wooden floor where urine passes vertically through openings in the floor and is routed to a soak pit; excreta and bulking agent remain on the false floor. The right side shows a urine diversion toilet where the urine is directly routed to a soak pit or urine storage container. An optional vent pipe was added to the left drawing. Source: Artwork by Linda Phillips. Reproduced from Mihelcic et al. (2009); with permission from ASCE. This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers. This material may be found at <https://ascelibrary.org/doi/book/10.1061/9780784409855>.

Figure 3. Constructed composting toilet in Panama (left) and urine diverting toilet in Burkina Faso (right). (left photo reprinted with permission of Jessica Mehl; right photo from Karin Ahlgren; reproduced with permission from Kvarnström et al. (2006) Urine Diversion: One Step Towards Sustainable Sanitation; EcoSanRes Programme.

The typical aspects of the composting process are:

1. primary aerobic (and sometimes anaerobic) microbiological decomposition that stabilizes the organic carbon and other organic matter to an odourless substance
2. during aerobic decomposition, heat generation can raise temperatures of the pile of excreta to thermophilic ($>40^{\circ}\text{C}$) or mesophilic ($20\text{--}40^{\circ}\text{C}$) ranges that enhances the die-off or inactivation of the pathogenic organisms
3. the biological degradation of the organics in the excreta may be enhanced directly through better oxygen transfer in the waste pile due to mixing or the presence of special types of earthworms (worm-composting) and other organisms (for example black-soldier flies)
4. well stabilised compost is a suitable product as a soil amendment and source of macro- and micronutrients favourable to plant growth; however, care should be taken to ensure the final product is safe (see Chapter on Sludge Management: Biosolids and Fecal Sludge)
5. the compost may be further stored, without further deterioration or environmental problems.

The typical aspects of the dry desiccating toilet

(sometimes designed and managed as a urine-diverting dry toilet (UDDT)) are:

1. desiccation is typically enhanced by addition of dry bulking materials (e.g., straw, wood ash, dry earth, lime, sawdust)
2. because reduction of moisture content is critical for pathogen inactivation, urine and anal cleansing water may be diverted from the toilet for collection or conveyance to the subsurface (Naughton et al. (2018) have reported that clogging of urine diversion tubing is a commonly reported issue so care needs to be made in maintenance and proper sizing of the tubing)
3. toilet design and operation can be integrated with urine diversion and storage that is followed by use of the urine as a fertilizer replacement (Kvarnström et al., 2006)
4. collected urine has been proposed as a source of free ammonia (NH_3) which has been found to destroy pathogens (Pecson et al., 2007; Trimmer et al., 2016)
5. the resulting desiccated excreta can be a suitable product as a soil amendment and a source of macro- and micronutrients favourable to plant growth. It is high in organic carbon; however, urine diversion will reduce the amount of nutrients in the product

because urine contains the majority of nitrogen, phosphorus, and potassium excreted by humans (Mihelcic et al., 2011). Care should be taken to ensure the final product is safe (see Chapter on Sludge Management: Biosolids and Fecal Sludge)

6. the desiccated solids may be further stored, without further deterioration or environmental problems.

Because composting and desiccating toilets can occur in many different forms, Table 1 is provided to show examples of other designs and associated processes. Vermicomposting and black soldier fly larvae composting toilets require extra attention to maintaining appropriate moisture, pH, temperature, and ammonia content so as not to kill the organisms (Hill and Baldwin, 2012).

Table 1. Examples of different toilets that employ composting and desiccating processes

Process	Description
Double Ventilated Improved Pit (VIP) Composting Toilet	<p>The Double VIP consists of two, side by side, ventilated improved pits (i.e., vault) usually constructed under the same super-structure with each pit having its own squat hole, seat or movable shared slab. One pit is used at a time while the other is completely sealed. The structure is either provided with two ventilation pipes (one for each pit) or one fitted to the pit in use. When the contents of the pit are 30 to 50 cm to the top the pit is sealed, and the second pit taken into use.</p> <p>After the non-use storage time of ideally 1.5 to 2 years, the contents of the first pit are removed (where they may be land applied) and that pit becomes operational again.</p>
Fossa-Alterna	<p>Similar to the double VIP but pits are shallower (1.5 m) and normally include the regular addition of bulking material during each use. Before the Fossa Alterna is used, the pit is lined with soil, straw, ash, etc. Following each defaecation, a quantity of soil is spread on top of the deposited excreta to enhance aerobic degradation and introduce additional organisms to convert the excreta into humus.</p>
Vermicomposting Toilets	<p>Involves a chamber where earthworms such as <i>Eisenia fetida</i> are added to a mixture of human feces, soil, and bulking material (e.g., vermicompost). Human feces are composted by both the activity of the earthworms consuming and excreting degraded material and the activity of other mesophilic organisms. Vermicomposting systems usually do not reach thermophilic temperatures (>40°C) in order to protect the earthworms (Yadev et al., 2010). Earthworms also provide aeration of the material. An adequate worm density of 0.03 +/- 0.04 g-worm/g-material was determined optimal by Hill and Baldwin (2012).</p>
Black Soldier Fly Larvae Composting Toilets	<p>Similar to vermicomposting but uses black soldier fly larvae, <i>Hermetia illucens</i> L. (Diptera: Stratiomyidae), instead of earth worms to consume and degrade human feces and organic waste. Composting chambers can be seeded with black soldier fly eggs or larvae. Following the larval stage, the black soldier fly prepupae will migrate out of the composting chamber into a separate, closed container connected to the main chamber by a pipe (Lalander et al., 2015). These prepupae may then be used as a protein source for animals and fish (Lalander et al., 2013).</p>
Urine Diverting Dry Toilet	<p>In a urine diverting toilet, the urine is collected and conveyed from the user interface separately from the solid feces. Drying material may be added to assist desiccation of the solid materials (Tilley et al., 2014).</p>

Additionally, a wide range of technologies for the collection, storage, and reuse of urine exists. This is not the focus of this chapter and there are many resources to assist a user in setting up a urine collection and reuse system (e.g., Kvarnström et al., 2006; Shaw, 2010; Tilley et al., 2014). As mentioned previously, urine may also be diverted into a soak pit, collected as a plant fertilizer, or added to excrement for sanitization.

Inputs and outputs of composting and dry desiccating toilet systems vary slightly based on the specific technology types provided in Table 1. Figures 4, 5, and 6 show some of these differences in inputs and outputs. The major inputs into composting chambers are feces, urine, anal wash water or dry anal cleansing material, and a bulking material that assists desiccation (e.g. ash, lime) (see Figure 4).

2.0 Inputs and Outputs for Composting

Figure 4. Typical inputs and outputs of a composting toilet (without urine diversion)

Tilley et al. (2014) and Berger (2011) discuss how the presence of particular inputs or lack of others (e.g., water and urine) impact operation and maintenance. In the case of a technology such as the Fossa Alterna, additional bulking material such as straw is added before use to line the pit. All inputs degrade over time to produce an output of composted human excrement. During the composting process gases such as carbon dioxide and methane may be produced (for amounts, see Orner and Mihelcic, 2018).

For a dry desiccating toilet, urine and anal cleansing water can be diverted or collected separately to reduce the moisture content of the material (see Figure 5). The inputs into this system shown in Figure 5 are the same as for the composting toilet in Figure 4 except there is a potentially an additional output of urine that can be reused as a fertilizer if the urine is not diverted to a subsurface soak pit.

Figure 5. Typical inputs and outputs of a dry desiccating toilet (with urine diversion)

Finally an additional input and output in vermicomposting toilets are organisms such as earthworms or black soldier flies (see Figure 6). In these cases urine and anal wash water needs to be partially diverted to create a suitable environment for the organisms by reducing the moisture

and/or ammonia concentration. If desiccation is promoted by addition of dry materials, the selected desiccants should not affect the organisms negatively. The output of vermicomposting systems are vermicompost, potentially additional organisms, and the separately collected urine.

Figure 6. Typical inputs and outputs of a vermicomposting toilet (with urine diversion)

3.0 Factors Affecting Pathogen Reduction in Composting and Dry Desiccation Toilets

The primary factors affecting pathogen removal of both composting and dry desiccating toilets are storage time, temperature, desiccation (measured by moisture content), and pH (Berger et al., 2011; Mehl et al., 2011; Trimmer et al., 2016). Other factors that assist pathogen removal are presence or addition of free ammonia (Pescon et al., 2007; Trimmer et al., 2016), and in composting toilets the carbon-to-nitrogen ratio of the pile of excrement (Mehl et al., 2011) and amount of aeration. These factors are discussed in the chapter on Sludge Management: Biosolids and Fecal Sludge.

These factors are influenced by different design and operational parameters, physical and chemical properties and processes, and environmental conditions as summarized in Figure 7. All factors and processes are interrelated and pathogen inactivation is most likely

achieved by a combination of inactivation mechanisms. For example, an important design and operational parameter is the type and amount of desiccant specified, because different desiccants result in different pH, porosity, and carbon-to-nitrogen ratio; all influence environmental conditions and pathogen reduction differently.

A higher pH ($\text{pH} > 9$) is recommended for enhanced pathogen removal but pH alone is not effective against helminths and thus an increase in temperature or other factor is needed (Pescon et al., 2007; Mehl et al., 2011). However, increasing the pH too high in a composting toilet may limit the overall biological reactions occurring within the pile of excreta to sufficiently raise the temperature of the excreta to a high enough value that promotes inactivation of pathogens (Mihelcic et al., 2009; Mehl et al., 2011).

Figure 7. Major factors affecting pathogen removal in composting and dry desiccating toilet systems

3.1 Design and Operational Parameters

Some of the main design and operational parameters that influence pathogen inactivation in both sanitation technologies are: (1) appropriate chamber size for adequate storage time given the number of users and expected temperature and moisture content in the pile of excrement, (2) inclusion of designs or materials that increase temperature or decrease moisture content, (3) mixing frequency and the method of mixing the pile of excreta, (4) whether urine is diverted from the feces, (5) type and amount of dry bulking material (i.e., desiccant) added that influences porosity of the pile (and thus aeration), moisture content, pH, and C/N ratio, and (6) presence or addition of

free ammonia. Due to space constraints, urine diversion is not a focus of this chapter as mentioned previously.

3.1.1 Chamber size, storage time, and modifications to enhance temperature, desiccation, and mixing

Regarding the importance of storage time, the Ct approach used for water disinfection (discussed in the Chemical Disinfectants chapter and Orner et al., 2017) can be applied in this case. In this approach, C is the concentration of disinfectant (e.g., greater temperature in the case of a composting toilet or lower moisture content for a dry desiccation toilet) achieved in the pile of

excrement and t is the contact time (i.e., the time the material is stored in the vault prior to land application). The Ct approach thus shows that storage time is a key parameter in pathogen destruction in both composting and dry desiccation toilets.

Most composting and dry desiccating toilets have a vault volume of at least 1 m³ and most likely a volume greater than that. Some desiccating toilets are designed to have a storage time as low as 60 days for situations where design modifications are made to enhance temperature (Cruz Espinoza, 2010); however, a minimum 6 to 18 month storage time is recommended in most situations.

Composting latrine chambers were originally designed for a 6 month storage time to achieve adequate pathogen removal. However, it is now recommended to increase the storage time to 1.5 to 2 years (Berger, 2011) because composting chambers have been found in the field to not reach high enough temperatures for destruction of resistant pathogens such as helminths over lower storage times (Mehl et al., 2011).

Any increase in chamber temperature that is transferred to the pile of excreta will enhance pathogen inactivation in both composting and dry desiccation toilets. Temperature can be enhanced in both types of toilets by design additions by insulating chambers to reduce conductive heat lost, external heating through addition of solar panels (Tonner-Klank et al., 2007; Cruz Espinoza, 2010), or use and orientation of transparent covers that focus the sun's energy to the chamber (Germer, 2011). A health risk study in El Salvador in fact concluded that solar composting latrines had far less prevalence of *Ascaris* (0.7 odds ratio) compared to regular desiccating latrines (15.5) and pit latrines (0.9) (Corrales et al., 2006).

In terms of materials that might elevate temperatures, Germer (2011) found slightly higher air temperatures (1.1-1.5°C higher), relative humidity, and airflow in toilet chambers covered with transparent, acrylic glass compared to those with non-transparent, metal covers. Newer prototypes of a solar dry toilet in El Salvador that was designed to promote increased temperature and desiccation were reported to achieve peak temperatures of 42°C and a moisture content of 15% (after 60 days of storage) (reported in Cruz Espinoza, 2010). However, Tonner-Klank et al. (2007) did not achieve thermophilic conditions in a composting toilet when adding insulation to chambers (4 cm thick, glass fiber mats) except for short periods of times when the study had optimized inputs of rye grass, sucrose, and fertilizer amendments to support biological activity.

Design considerations that impact aeration or mixing are important for composting toilets. This is because mixing of the composting chamber contents increases aeration and thus microbial activity. The type of and amount of dry bulking material (i.e., desiccant) added to the pile can also improve aeration by increasing the porosity of the pile of excrement. Some have proposed increasing aeration by adding a vent pipe (as in a VIP pit toilet) to increase the flow of air across the surface of the pile of excrement.

However, this is not expected to increase the air flow significantly into the pile except in cases where sufficient bulking material is added to achieve high porosity in the pile of excreta.

Aeration can also be achieved by turning the pile. Composting latrines usually have rear doors where this can be performed by a user. Opening a rear door and safely mixing the pile of excreta may not be easy and convenient for a toilet owner. Some rear doors are partially mortared, some are just planks of wood wedged into the open space, while doors with metal doors and hinges may be prohibitively expensive to beneficiaries. Others have proposed designs with corkscrew components to mix the waste. These mixing methods can expose the user to pathogens or are not performed regularly, if at all, by the users. Also, it is difficult to uniformly mix the compost and some areas may be left unmixed. Consideration of mixing is thus an important design consideration and consideration of the reality that contents might not be mixed is important to consider when thinking how operation of a composting toilet impacts environmental conditions within the pile of excreta and pathogen destruction.

3.2 Operational Properties that Influence Environmental Factors that Lead to Pathogen Reduction

3.2.1 Temperature

A dry desiccating toilet can only enhance temperature of the pile of excreta through design modifications discussed previously. However, in a composting toilet, achieving a temperature in the pile of excrement greater than ambient can also be attained from the aerobic biological decomposition of organic carbon and other organic matter in the excrement. This microbiologically mediated oxidation reaction produces heat. The efficiency of this reaction (and thus an increase in temperature) is important in determining the effectiveness of the composting process on pathogen inactivation.

Cairncross and Feachem (1993) have presented an excellent diagram showing the importance of contact time and temperature on pathogen destruction (the figure is reproduced in books such as Mihelcic et al, 2009 and is also found on the Internet; for example, <https://www.sanitationhealthintransition.com/new-page-2/>). This figure shows that while many pathogens are destroyed at ambient temperatures experienced in equatorial locations with sufficient contact (storage) times, for the most resistant pathogens (e.g., *Ascaris ova*) temperatures greater than ≈45°C would need to be maintained for contact periods of at least 6 months.

In fact, Feachem et al. (1983) stated that two weeks of exposure at 55°C would reduce all pathogens to harmless levels and Guardabassi et al. (2003) suggested one hour of contact time at 70°C as sufficient. The World Health Organization (WHO) recommends that the excreta in a composting toilet waste should be exposed to 50°C for one to four weeks and then stored for an additional 2 to 4

months (WHO, 2006).

Because the composting process is an exothermic biological process it should theoretically achieve thermophilic temperatures. Unfortunately, in many field studies of composting toilets, the temperature achieved in the excreta pile is often close to ambient levels (Redlinger et al., 2001; Tønner-Klank et al., 2007; Jensen et al., 2009; Mehl et al., 2011; Sossou et al., 2016). An example from Panama illustrates this where only 32% of composting toilets achieved excreta pile temperatures above ambient temperature and only 2% attained temperatures above 40°C (Mehl et al., 2011).

Temperature is particularly important for destruction of *Ascaris ova* (e.g., Pescon et al., 2007; Manser et al., 2015). Lower temperatures (e.g., in the mesophilic range) do not mean that pathogen die-off does not occur. It just means the destruction occurs at a lower than expected efficiency and thus contact time becomes more important. Modeling can be employed to estimate rates of *Ascaris* inactivation for example (e.g., Fidjeland, et al., 2015; Manser et al., 2016).

Several operational factors influence temperature in a composting toilet: (1) aeration (controlled by mixing and the porosity of the pile), (2) partial desiccation to reduce the moisture content of the pile but not so much that it kills off the microorganisms that are degrading the organic carbon, and, (3) an optimum carbon-to-nitrogen (C/N) ratio. These items are discussed in the next subsection where types of bulking agents (i.e., desiccants) are discussed.

3.2.2 Types of desiccants and their impact on moisture content, pH, and carbon-to-nitrogen ratio

For the use of a composting or dry desiccating toilet, users are advised to add some form of dry bulking material after each use. These materials are commonly referred to as desiccants. Table 2 provides information on some important properties of desiccants and how addition of desiccant will aid pathogen inactivation. Desiccants have a secondary advantage which is they also help to reduce the presence of insects and odors (Niwigaba et al., 2009; Magri et al., 2013).

Table 2. Properties of dry materials (desiccants) added to toilets and how they may aid pathogen inactivation

Property of Dry Material	What the Dry Material Does to Aid Pathogen Inactivation
Bulky	Provides porosity to excreta pile which improves aeration, and thus biological activity that can increase temperature
Dry	Along with urine diversion and elimination or minimal use of anal cleansing water, can reduce moisture content and lead to desiccation of pathogens. Stored material should be kept out of rain.
Basic pH	Lime and other dry materials such as some ashes (e.g., wood ash) are basic, so they can raise pH of the excreta pile. For example, wood ash has a pH of 9.4 to 11.3, rice husks 10.6, and lime 10.3. In contrast, sawdust has a pH that ranges from acidic (4.5) to just a little above neutral (7.8) (Mihelcic et al., 2009)
Carbon Rich	Some dry materials such as sawdust, wheat straw and oat straw have high C/N ratios of 48 to 500 (dry mass basis) that can be used to raise the C/N ratio to an optimal value of 20:1 to 30:1. Thus they can be used to not only enhance porosity and reduce moisture, but also increase the C/N ratio.

The type of material and the amount added after each use has a large impact on pathogen destruction and whether the toilet performs as a dry desiccation or composting toilet. Common desiccants are ash (from burning wood or other materials), dry soil or sand, dry leaves, dry grass, rice husks, lime (quicklime or hydrated lime), crushed oyster shells, and shea nut shells. Selection of a desiccant is typically determined by what is locally and seasonally available and is cost effective (Mehl et al., 2011; Magri et al., 2013; Sossou et al., 2014).

Selection of an appropriate desiccant should be

carefully linked to the toilet operation and primary environmental factor and mechanism that leads to pathogen destruction. This is because some desiccants absorb moisture well, some are good sources of carbon, and some will increase the mixture's pH. Some desiccants may perform multiple functions. And for operation of a composting toilet, a bulky desiccant will support aeration in the chamber's contents through increasing the porosity of the pile. Another item to consider is what is a sufficient volume of desiccant to add after each use (e.g., 1 or 2 cups, 1 or 2 handfuls, or more?).

3.2.2.1 Moisture content

Desiccants are important in both composting and dry desiccating toilets to adjust the moisture content to an optimal level to promote pathogen inactivation. In a composting toilet, an optimal moisture content to promote biological activity that gives off heat is $\approx 45\text{--}65\%$ (USEPA, 1994; Berger, 2011; Mihelcic et al. 2009). As moisture content drops below 25% in a composting toilet, the microbial activity in the pile decreases and stops around 10% (Berger, 2011).

Desiccation to low values of moisture content is a well-established method to inactivate pathogens in sludge (through drying of sludge) as discussed in the chapter on Sludge Management: Biosolids and Fecal Sludge. In the drying of sludge, moisture contents of 10-30% are targeted to achieve pathogen destruction. For a dry desiccating toilet the moisture content should similarly be reduced to the low range of 10-15% to achieve pathogen destruction (note this lower value will differ for different pathogens).

3.2.2.2 pH

Desiccants are also used to raise the pH of the pile of excreta to enhance pathogen inactivation. Common desiccants that will raise the pH of the pile are wood ash, burnt rice husks, and lime. For example, mixing lime with feces is known to be an effective process to reduce pathogen concentrations. Accordingly, achieving a pH of > 12 is a well-established method to inactivate pathogens in sludge as discussed in the chapter on Sludge Management: Biosolids and Fecal Sludge.

The type of desiccant and amount added per use are obviously key factors in determining if sufficient pH is reached. In addition, as with temperature, the storage time of the resulting mixture also influences pathogen concentrations. For example, Endale et al. (2012) did not detect any fecal coliforms in feces obtained from a urine diverting toilet after 30 days of storage after the addition of wood ash (a pH of 9 was achieved). With the addition of lime (which achieved a higher pH of 11.3), no fecal coliforms were detected after 1 day. Vu-Van et al. (2017) found different combinations of lime, risk husk, and aeration effective at reducing *Ascaris lumbricoides* in Vietnam. The best combination was 10% lime with aeration.

Wood ash has been found to be effective in pathogen destruction due to a combination of elevating pH (the ash had initial pH of 12.4) and decreasing the moisture content (Magri et al., 2013; Niwagaba et al., 2009). Oyster shells (pH of ≈ 8.8) are alkaline but when used solely were found to not sufficiently increase pH of feces to efficiently enhance microbial die-off (e.g. pH of 5.85) (Magri et al., 2013). However, oyster shells in combination with wood ash and urea can be effective at reducing pathogens (Magri et al., 2013). Crushing the shells should improve their effectiveness. Moreover, regarding use of ash, the effectiveness of the ash will depend not only on the type of ash (not all ashes are highly basic) including the burning temperature and chemical composition (e.g. carbon and hydroxides) of the material (Hijikata et al., 2016). Usually

wood ash and ash produced at a higher burning temperature are preferable compared to ash from grass, rice, or mixed ash that have lower alkaline properties (Hijikata et al., 2016).

Niwagaba et al. (2009) detected *E. coli* in feces from urine diversion dry toilets with sawdust desiccant after two months but did not for those where wood ash was added and also found on average $2 \log_{10}$ higher concentrations of *Enterococcus* spp. in excreta from a urine diverting dry toilet with use of sawdust as the desiccant than wood ash. In that study, the sawdust had a lower pH (5.5) than the charcoal ash (12.5) (Niwagaba et al., 2009). Sossou et al. (2014) suggested that rice husk charcoal ash may be a more effective desiccant in supporting fundamental microorganism inactivation mechanisms than sawdust, rice husk, and charcoal. Rice husk and sawdust are also reported to damage the outer membrane of *E. coli* while ash inactivates by damaging the outer membrane and/or enzyme activity and, thus, may be more lethal (Sossou et al., 2014). Similarly, Hijikata et al. (2016) found that ash (wood, rice straw, and mix of ashes with oyster shell) and lime damage the outer membrane and enzyme activities of *E. coli* and in MS2 coliphage reduce infectivity.

3.2.2.3 Carbon to nitrogen (C/N) ratio

The C/N ratio is not an important parameter in the operation of a dry desiccating toilet. However, it is important for proper operation of a composting toilet. Feces have a C/N ratio of 6-10 and urine only 0.8 (dry mass basis). The composting process is most effective at achieving an increased temperature in the pile of excreta when the C/N ratio is raised to 20:1 to 30:1 (discussed in the chapter on Sludge Management: Biosolids and Fecal Sludge). Furthermore, the biological processes that occurs during composting prefer a near neutral pH (6.5 to 7.5). Thus a desiccant added to a composting toilet should: (1) serve as a bulking agent to increase porosity of the pile of excreta (to improve aeration), (2) maintain an appropriate moisture content ($\approx 45\text{--}65\%$) to support biological activity, (3) maintain a near neutral pH, and (4) raise the C/N ratio to 20:1 to 30:1.

Because the C/N ratio of human feces is lower than desired, it is important to add an appropriate amount of an easily degradable organic carbon to increase the C/N ratio. Waste materials that provide good bulking properties, do not raise pH significantly, and have a high C/N ratio include sawdust (C/N of 200-500), wheat straw (130-150), oat straw (48), and dry leaves or grass (however fresh yard waste only has a C/N of 23). If possible, these desiccants should be collected and stored in the absence of rain.

Wood ash is a widely used desiccant because it is cost effective and readily available in many locations. It reduces the moisture in toilets and because of its higher alkaline properties is able to raise the pH of the pile of excreta. However, it only has a C/N ratio of 25. Thus, though it will increase the C/N ratio somewhat, overall, it is less appropriate in promoting the composting process compared to some previously mentioned desiccants. A mixture of high C/N ratio desiccants (saw dust) and wood ash though can

achieve multiple objectives in enhancing temperatures, reducing moisture content, and maintaining a slightly basic pH which can support pathogen destruction (Mehl et al., 2011).

Mehl et al. (2011) provides a discussion on the complexity of sorting out the correct type of desiccant for operating a composting toilet as well as the correct amount of material to add. Mihelcic et al. (2009) provide a detailed example on calculating the correct amount of a particular desiccant to achieve a desired C/N ratio.

Because some composting latrines, as currently designed and operated, may not achieve sufficient temperatures to inactivate all pathogens, other physical-chemical factors such as enhancing pH and desiccation may play the primary role in pathogen destruction in composting latrines/toilets (Tønner-Klank et al., 2007). For example, when studying 90 composting toilets in Mexico, Redlinger et al. (2001) found that desiccation was the primary mechanism for fecal coliform reduction. Desiccation may also occur to a greater extent in both composting and dry desiccating toilets near the top of unsealed or ventilated vaults exposed to the air. In fact, Tønner-Klank et al. (2007) found smaller concentrations of bacteria, viruses, and helminths in excreta samples collected at the top of the composting chamber compared to the middle and the bottom of the pile of excrement.

3.2.2.4 Free ammonia (NH₃)

Addition of urea or human urine to desiccated or composted feces can aid in pathogen reduction. This is because both contain or will produce ammonia, which can provide an additional level of pathogen reduction to desiccated or composted excreta. This can be accomplished in the field by addition of urine or synthetic urea (CO(NH₂)₂) and increasing the pH of the mixture. Raising pH is accomplished by the addition of wood ash, lime, or other pH-increasing materials to shift the ammonia equilibrium so more of the total ammonia (NH₄⁺ + NH₃) is present as the NH₃ species (Pescon et al., 2007; Fidjeland et al., 2015; Trimmer et al., 2016). This is because the equilibrium constant (K_a) for the chemical reaction between the acid NH₄⁺ and its conjugate base NH₃ is 9.3.

It is proposed that free ammonia (NH₃) is able to inactivate pathogens, including *Ascaris*, by penetrating their membranes and disrupting the organism's internal chemistry (Fidjeland et al., 2015). For viruses, ammonia may reduce their infectivity through protein degradation (Guardabassi et al., 2003).

Cruz Espinoza (2010) added synthetic urea to material simulating the excrement obtained from a dry desiccating toilet and found the minimum ammonia concentration (as

NH₃) to inactivate 100% of *Ascaris suum* ova was 1,350 ppm for 28-35°C and 794 ppm at 40°C. However, synthetic urea may be too expensive to use as an additive in developing countries so stored human urine may be another option (Trimmer et al., 2016). Trimmer et al. (2016) proposed an additional 2 log₁₀ inactivation of *Ascaris* ova can be achieved with a mixture of two parts human urine and one part of toilet excrement (that was obtained from a urine-diverting toilet after 2-3 months of storage).

Another important consideration for ammonia sanitation is use of airtight storage to prevent loss of ammonia in collected urine or ammonia treated feces via emissions to the atmosphere (Fidjeland et al., 2015). This loss not only adversely impacts the inactivation of pathogens but can also cause nuisance odors.

Magri et al. (2013) found that a combinations of different desiccants (ash and oyster shell) and urea was effective in reducing pathogens (*Enterococcus faecalis*, *Salmonella enterica*, bacteriophages, and *Ascaris suum*) compared to controls with no additives or only desiccant or only urea. The most effective combination was 150% of an equal oyster shell and ash mixture with 0.5% urea to the wet mass of feces. A combination of ash and oyster shell was more effective than just oyster because the higher pH achieved by the addition of ash. This mixture corresponded to a reduction in bacteriophage MS2 by 6.5-7.5 log₁₀ in 130 days (Magri et al., 2013).

3.0 Key Factors and Strategies to Enhance Pathogen Reduction

The removal of pathogens in a composting or dry desiccating toilet depends on a number of environmental factors as well as engineering design and operation and maintenance practices. In a dry desiccating toilet the most important factor is achieving low moisture content with higher temperatures and also raising pH to support pathogen removal. The composted or desiccated excreta could be further treated with addition of ammonia.

For a composting toilet, the factors that are expected to have the largest impact on pathogen removal: (1) retention (storage) time, (2) temperature, (3) aeration through addition of bulky desiccants, and (4) C/N ratio. High pH can also be used to achieve pathogen destruction, however, only some specific desiccants (such as lime or wood ash) will achieve a pH that approaches 12 that is recommended to achieve significant pathogen destruction and in this case would lower the biological activity that leads to higher temperatures. In either case, it is expected that several environmental factors will lead to multiple mechanisms of pathogen destruction. These factors and their importance are summarized in Table 3.

Table 3. Summary of key factors and strategies to enhance pathogen reduction efficiencies in composting and dry desiccating toilet systems

Factor	Pathogen Removal is ↑ Enhanced or ↓ Reduced Under the Following Conditions:	Pathogen Groups Primarily Affected			
		Bacteria	Viruses	Protists	Helminths
Temperature	Higher Temperature = ↑ Pathogen Removal	×× ^a	××	× ^b	×
Storage Time	Longer Storage Time = ↑ Pathogen Removal	××	××	××	××
pH ^c	↑ pH = ↑ Pathogen Removal	××	××	×	×
C/N Ratio ^d	↑ C/N ratio = ↑ Pathogen Removal	×	×	×	×
Ammonia	↑ Ammonia = ↑ Pathogen Removal	×	×	×	×
Moisture ^e	Lower moisture content = ↑ Pathogen Removal	××	××	××	××

^a ×× = most affected; ^b × = moderately affected; ^c = too high of pH in a composting toilet will adversely impact performance; ^d = applicable to composting toilet; ^e = too low moisture content in a composting toilet will adversely impact performance

Studies on pathogen reduction in composting and dry desiccating toilets often focus on helminths such as *Ascaris lumbricoides* because the eggs of this species are highly resistant to environmental stressors and thus often function as a limiting case for determining minimum required excreta storage/inactivation times. For dry desiccating toilets, significant log removal is expected. A high pH, low moisture content, and a storage time of 6-12 months with addition of wood ash or lime, one can achieve up to a 6 log₁₀ reduction of bacteria, 4 log₁₀ reduction in viruses, and complete removal of protozoa and helminths (Stenstrom et al., 2011). It is expected that that a storage time of 1.5 to 2 years will completely remove remaining bacteria and viruses (Stenstrom et al., 2011). Other studies using wood ash as a desiccant reported 8 log₁₀ reduction of viruses and complete removal of *Ascaris* at temperatures of 31-37°C, pH between 8.5 and 10.3, and moisture content between 24 and 55 percent (Carlander and Westerell, 1999; Chien et al., 2001).

In composting toilets, all pathogens are expected to be removed if thermophilic temperatures are achieved and a contact time of at least 1.5 years is provided for pathogens of concern. However, these elevated temperatures may be difficult to obtain (Epstein, 1997). A study of urine-diverting composting toilets in six communities in Panama indicated that pathogens, mostly helminths such as *Ascaris lumbricoides*, were present in excreta after six months. This was likely because of low storage times and lower than expected temperatures in the composting excreta resulting from an insufficient C/N ratio and poor mixing of the excreta (Mehl et al., 2011). Temperature can be enhanced through options such as better mixing and addition of sufficient amounts of carbon rich desiccants (Mehl et al., 2011) and solar heating (Stenstrom et al., 2011).

4.0 Impact on Surrounding Environment (Groundwater and Surface Water)

Because most composting and dry desiccating toilets are located above ground, they are not expected to pose a risk to groundwater during user operation as unlined pit toilets do (see Pit Toilet chapter). One exception is the

Fossa Alterna technology which may have a slight impact if incorrectly sited; however, due to its shallow depth this may not present as much of risk as standard unlined pit toilets. If, however, the chambers of a composting and dry desiccating toilet are not sealed properly they may leak and contaminate surface water or groundwater, especially during the rainy season.

It may also be more difficult to apply composted or desiccated excreta safely during a rainy season because of potential for stormwater runoff. If composted and desiccated excreta are applied to soil, it should be buried sufficiently below the ground surface (below 10 cm). Furthermore, if placed on top of soil, rain may cause the compost and any pathogens that were not destroyed during the desiccating or composting process to run off into surface water and surrounding environments where humans come into closer contact. Urine diversion can convey collected urine to the subsurface and may contaminate shallow groundwater with ammonia that is transformed to nitrate (as unlined pit toilets can do) but this was not a focus of this chapter.

Because temperature and moisture content are some of the major factors for pathogen removal in composting and desiccating toilets, these are important environmental factors related to the climate the toilets are constructed in. As stated previously, many composting toilets do not reach thermophilic conditions and temperatures are similar to ambient conditions (Redlinger et al., 2001; Mehl et al., 2011). Thus, composting and dry desiccating toilets are expected to achieve greater pathogen removal in hotter and drier climates because pathogens are more efficiently removed at higher temperatures and in drier conditions that promote desiccation. For example, low temperatures of 10°C and 20°C may be insufficient to kill *Ascaris* eggs within a one year storage time (Hawksworth et al., 2010). A study comparing the die-off rate and inactivation of *Ascaris* eggs at different temperatures and relative humidity found that below 60°C, relative humidity became important for pathogen die off (Hawksworth et al., 2010). Furthermore, areas with greater amounts of rainfall may infiltrate chambers and cause higher moisture content in general.

5.0 Epidemiology and Health Risk Evidence

There are important, potential epidemiological and health risks associated with composting and dry desiccating toilets for both those who operate and maintain the systems and those that consume food fertilized with the compost or urine fertilizer. Stenström et al. (2011) is an excellent resource that provides detail on microbial exposure and health assessment of various sanitation technologies. In summary, proper safety gear (e.g. masks, gloves, and boots) should be worn by those mixing, removing, and applying compost. Additionally, compost should be used for tree and fodder crops and not fruits and vegetables that are low to the ground that may become contaminated with the compost if pathogen destruction was not complete. If applied to fruits and vegetables, it should be 90-120 days before harvest.

Even if the proper operation and maintenance are followed for composting latrines, there are certain recommendations for the mixing, removal and application of compost on crops that will further help reduce pathogens and human exposure to them. First, it is better to remove compost during the dry season than rainy season so there will not be as much potential runoff of the material when applied. Next, when removing and mixing compost, proper safety equipment should be worn such as gloves, boots, and masks.

The health risk for dry desiccating toilets varies for users, workers, and community members. Users of toilets are never exposed because the dehydration vault contains the feces; therefore, the overall level of risk is low. One worker may be exposed infrequently; therefore, the worker's risk is low. A variable number of community members may be exposed to health risk depending on how the urine collection is handled, resulting in a medium level of risk due to the potential of contaminated urine (Stenström et al., 2011).

6.0 Conclusions

Composting and dry desiccating toilets (also referred to as latrines) are popular onsite sanitation technologies where the contents (i.e., excreta) can be reused and returned to the local environment within the sanitation

chain. The removal of pathogens in a composting or dry desiccating toilet depends on a number of environmental factors as well as engineering design and operation and maintenance practices. In either case, it is expected that several environmental factors will lead to multiple mechanisms of pathogen destruction.

A composting toilet is designed and operated to enhance conditions within the waste pile of human excreta to promote aerobic biological processes that gives off heat, which in turn can inactivate pathogens. For a composting toilet, the factors that are expected to have the largest impact on pathogen removal: (1) retention (storage) time, (2) temperature, (3) aeration through addition of bulky desiccants, and (4) C/N ratio. High pH can also be used to achieve pathogen destruction, however, only some specific desiccants (such as lime or wood ash) will achieve a pH that approaches 12 that is recommended to achieve significant pathogen destruction.

A dry desiccating toilet is designed and operated to enhance the physical process of desiccation (or drying) of the waste pile that contains human excreta, which in turn can inactivate pathogens. In a dry desiccating toilet the most important factors to achieve a low moisture content is addition of dry desiccant and a higher temperature. Higher retention (storage) times will also improve pathogen inactivation. Increased pH caused by desiccant addition also supports pathogen removal. The desiccated excreta can be further treated with addition of ammonia.

For dry desiccating toilets, significant log removal is expected. At high pH, low moisture content, and a storage time of 6-12 months with addition of wood ash or lime, one can achieve up to a 6 log₁₀ reduction of bacteria, 4 log₁₀ reduction in viruses, and complete removal of protozoa and helminths (Stenström et al., 2011). It is expected that that a storage time of 1.5 to 2 years will completely remove remaining bacteria and viruses (Stenström et al., 2011). In a composting toilet, all pathogens are expected to be removed if thermophilic temperatures (>40°C) are achieved and a contact time of at least 1.5 years is provided. However, this elevated temperature may be difficult to obtain in the field without consideration of how design and operation impact the composting process and resulting pathogen removal.

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