Review

A Review of Dry Sanitation Systems

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Abstract: Dry sanitation systems (waterless or composting toilets) have been used since the 1970s. Their use has received acceptance in rural regions of Europe and the United States. Some of the advantages of dry sanitation systems include their waterless nature, their low energy requirement and the creation of fertilizer as an added value product. Moreover, the use of such a system is a sustainable sanitation approach that may reduce the burden on infrastructure and provide sanitation to the 2.5 billion people worldwide who do not currently have access to it. The critical factors when choosing a dry sanitation system and their optimum parameters include aeration, moisture content (50%–60%), temperature (40–65 °C), carbon to nitrogen ratio (25–35), pH (5.5–8.0) and porosity (35%–50%). The temperature–time criterion approach is the most common method used to evaluate the stability and safety of the compost as a fertilizer. The risks of handling the waste after 12 months of composting have been calculated as low. Here, we have reviewed and assessed the features of dry sanitation systems currently available, focusing on those designed for and operated in remote areas such as national parks and tourist destinations and, more importantly, in rural areas in developing countries or refugee shelters where water/sanitation may be scarce.

Keywords: dry sanitation systems; waterless toilets; composting toilets; fertilizer; sustainability

1. Introduction

The energy invested to produce drinking water for use in a flush toilet for wet sanitation is not a sustainable activity; there is a requirement for alternative sanitation options to be trialled and eventually put in place [1]. Although the use of greywater (water waste from all household activities except sewage) [2] and rainwater is one option currently being used to save precious drinkable water, this option is still linked to a central wet sanitation system. Therefore, an option independent from the central wet infrastructure, such as the waterless or composting toilet, which represents dry sanitation systems, remains a key option.

Dry sanitation systems have been used in the developed world since Rikard Lidstrom invented the first composting toilet in 1939 in Tyreso, Sweden. A patent was created in 1962, and the company Clivus Multrum started selling models in the 1970s.

Currently, there are manufacturers of dry sanitation systems in several countries around the world including Japan, the United States, Germany, Sweden and France [3–6]. Moreover, organizations promote both the manufacture and use of waterless and composting toilets in developing countries (e.g., Semarnat & Tierramor in Mexico), and there are also manuals for their construction [7]. The main

microorganisms reported to be involved in the composting process are bacteria, actinobacteria and fungi [8].

Dry sanitation systems have been mainly used in rural areas and those areas with water shortages [9–11], but their use in urban areas has also been studied [9]. A commercially available dry sanitation system (bio-toilet) has also been used in Japan in public parks, sightseeing locations and households [12].

The main advantages of the dry sanitation systems are the decentralization of a water system and the production of fertilizer for plants. This activity falls within the sustainability approaches required nowadays since the increasing world population (7.7 billion in 2020) is constantly adding more pressure to the already limited drinking water resources. More importantly, it could lower the number of gastrointestinal infections recorded in rural areas. Increased sanitation can be cost-beneficial; it has been observed that the return of \$1 invested in sanitation was in the range of \$11.6–22.9 [13]. However, information on dry sanitation systems is still scarce and there is a lack of peer-reviewed literature. Therefore, this review is based on the available peer-reviewed and grey literature [14,15] and aims to compile information on the different types of commercially available dry sanitation systems with an emphasis on the large-capacity waterless toilets that require the least maintenance. Such models could provide an alternative for the growing ecotourism industry, ski and hiking areas, refugee shelters or rural/impooverished areas in developing countries suffering water shortages.

2. Types of Dry Sanitation Systems

Dry sanitation systems can be classified as self-contained or central, single or multi-layered chamber tank, mixing device, urine separating, electric or solar, and completely waterless or with low water usage (Table 1). Such features mainly depend on their intended location and their circumstances; e.g., solar-powered, with a multi-layer chamber and completely waterless will be selected for remote areas in national parks, while self-contained, electric and single layer could be used in a building within an urban setting.

Table 1. Types of dry sanitation systems available.

Type	Energy	Chamber Tank	Water Usage	Bulking Agent
Self-contained	Solar	Single layer	Waterless	Needed
Central	Electric	Multi-layer	Low water usage	Not needed

2.1. Self-Contained or Central

Self-contained refers to those where the composting chamber and the toilet are one unit. Central composting toilets have a much larger tank and can be connected to multiple toilets. Vertical piping is needed to direct the faecal matter to the composting tank.

2.2. Single or Multi-Chambered Tank

Single tank refers to toilets with only one chamber and where old and fresh waste is composted. Clivus Multrum, Phoenix and Sun-Mar are examples of commercial brands with single-chamber tank toilets.

Multi-chambered composting tanks usually have two or three chambers and are designed for the different stages of composting (composting, evaporating and finishing). Carousel composting is another version with four chambers; every time a chamber tank is full, the carousel is moved to the next chamber to collect fresh waste. Thus, when the fourth chamber is filled, the waste in the first chamber has been composted and is ready to be removed [16]. The Eco-Tech Carousel and BioLet companies have these models. Another model is a bio-drum that rotates the waste into different chambers, each for a different composting stage.

2.3. Electric and Non-Electric Toilets

Electricity is used for fans, heating systems or to create a vacuum. The fan draws the air into the toilet, eliminating odours in the bathroom. In some dry sanitation systems, the air inside the toilet is heated and evaporates the excess liquid (BioLet). When a vacuum is created to convey the waste, a water flush is also usually used. Examples of electric toilets are the Phoenix and Nature-loo.

2.4. Urine Separating and Combined Collection Toilets

It has been estimated that 500 L of urine and 50 L of faeces are produced per person annually [17]. Separating the urine has the advantage of reducing the odours and excess liquid in the composting pile and has been recommended previously [18]. Moreover, the urine can be used as a fertilizer due to its low pathogen concentration and high nitrogen, potassium and phosphorus content [19]. Another study also found that vermicomposting toilets that separate the urine (or no-mix toilets) performed better in mass reduction, pathogen destruction, compost quality and operational cost than the ones not separating the waste [20].

3. Factors Affecting Aerobic Composting Toilets

In general, a dry sanitation system works by converting the waste into compost that can later be used as fertilizer for crops. Compost is a mixture of decomposing manure or vegetable waste, where the decomposition is carried out aerobically by specific microorganisms that include bacteria, fungi and actinomycetes [21,22]. Four stages of the compost can be defined: (1) the mesophilic phase, (2) the thermophilic phase, (3) the cooling phase and 4) the curing phase [23]. In the initial decomposing stage, mesophilic bacteria such as *Escherichia coli* and other Enterobacteria produce CO₂ and energy that is partially used for reproduction and growth and the rest is released as heat, raising the compost temperature to 44 °C. This is followed by the thermophilic microorganisms that further raise the temperature to 65 °C, and in this process the pathogens are killed. At the cooling phase, the mesophilic microorganisms take over again and continue digesting the more resistant organic materials. Humus is produced by fungi and other microorganisms such as earthworms and sowbugs. The last step in the composting process called curing, aging or maturing is long and should last around 12 months after the thermophilic phase to make sure pathogens have been destroyed [23]. This was confirmed by a study that found the risks of handling the compost after 12 months are low. This study is described in more detail below [24].

The microbial diversity in compost has been elucidated and is shown in Table 2. A more recent study on a hot synthetic compost has confirmed the dominance of *Bacillus* [25] among other genera. As mentioned, it is the mesophilic and thermophilic bacteria that increase the temperature, followed by the actinomycetes and, in turn, by fungi during the later stages of the process. Although the appropriate choice of microorganisms is critical for the compost, factors such as temperature, aeration, pH, carbon/nitrogen ratio and moisture can affect the proper operation of the compost and, therefore, are discussed below. Optimum values for these factors are shown in Table 3.

Table 2. The microbial diversity in a compost. Adapted from [21].

Actinomycetes	Fungi	Bacteria
<i>Actinobifida chromogena</i>		<i>Alcaligenes faecalis</i>
<i>Microbispora bispore</i>		<i>Bacillus brevis</i>
<i>Micropolyspora faeni</i>		<i>B. circulans</i> complex
<i>Nocardia</i> sp.	<i>Aspergillus fumigatus</i>	<i>B. coagulans</i> type A
<i>Pseudonocardia thermophila</i>	<i>Humicola grisea</i>	<i>B. coagulans</i> type B
<i>Streptomyces rectus</i>	<i>H. insolens</i>	<i>B. licheniformis</i>
<i>S. thermofuscus</i>	<i>H. lanuginosa</i>	<i>B. megaterium</i>
<i>S. thermoviolaceus</i>	<i>Malbranchea pulchella</i>	<i>B. pumilus</i>
<i>S. thermovulgaris</i>	<i>Myriococcum thermophilum</i>	<i>B. sphaericus</i>
<i>S. violaceus-ruber</i>	<i>Paecilomyces variotti</i>	<i>B. stearothermophilus</i>
<i>Thermoactinomyces sacchari</i>	<i>Papulaspora thermophila</i>	<i>B. subtilis</i>
<i>T. vulgaris</i>	<i>Scytalidium thermophilum</i>	<i>Clostridium thermocellum</i>
<i>Thermomonospora curvata</i>	<i>Sporotrichum thermophile</i>	<i>Escherichia coli</i>
<i>T. viridis</i>		<i>Flavobacterium</i> sp.
		<i>Pseudomonas</i> sp.
		<i>Serratia</i> sp.
		<i>Thermus</i> sp.

Table 3. Optimum values of factors affecting aerobic composting.

Carbon/Nitrogen Ratio	Aeration	pH	Temperature	Particle Size and Porosity	Moisture Content
25–35	15% to 20% range	5.5 to 8.0.	19–65 °C	35%–50% porosity	50%–60%

3.1. Carbon/Nitrogen Ratio

The carbon and nitrogen composition of human faeces decreases during the composting process. Around 66% of faecal nitrogen converts to ammonia while 34% remains as biologically inert nitrogen [26]. Similarly, 80% of carbon converts to CO₂ while 20% stays in the compost [27]. Thus, the loss of N and C as gas emissions (ammonia and CO₂) reduces the nutrient and agronomic value of the compost. However, high mineralization results in a mature compost due to reduced leaching and volatilization when applied to plants [28]. The addition of bulking agents with a high lignocellulose content (e.g., sawdust) decreases the loss of nitrogen [29]. The C and N loss depends on the bulking agent and the composting process [28].

A carbon to nitrogen ratio of 25–35 has been recommended for the composting of municipal waste and sewage sludge [30]. The C:N ratio in human faeces is deficient in carbon (C:N = 8). Therefore, to increase the carbon content in the compost, several bulking agents such as sawdust, wood chips, grass cuttings, dried leaves, kitchen waste and toilet paper can be added [31].

3.2. Aeration

Aerobic conditions should be maintained since a lack of oxygen produces odour issues and the composting rate is lowered. However, an excess of airflow may remove water vapour from the compost. The amount of air is inversely proportional to that of the moisture. Previous studies have suggested an optimum oxygen concentration within the 15% to 20% range [32].

3.3. pH

It has been observed that pH usually decreases during the composting process due to the conversion of carbonaceous material to organic acidic intermediates; pH also increases as the temperature increases [30]. Thus, studies have recommended an optimum pH range of 5.5 to 8.0 [30,32], while a pH within the 6.7–9.0 range has been suggested for animal manure composting and prevents nitrogen loss by ammonia [29].

3.4. Temperature

Composting is performed initially by mesophilic organisms at a temperature range of 19–45 °C and is followed by thermophilic organisms at a temperature above 45 °C, increasing the composting rate [23,33]. Most of the organic degradation and pathogen destruction occurs within the 50–65 °C range [28,34]. As the temperature reduces, mesophilic organisms take over again and break down the remaining compounds.

Optimum temperatures for composting have been suggested as 40–65 °C [30] and 60 °C [35], but temperatures >65 °C prevent the composting process [36]. An optimum temperature can be obtained by insulation, turning and electric heaters [37,38]. Turning the compost is an efficient way to obtain the optimum temperature. The Envirolet manufacturers claim that their models are ideal to work in low temperatures.

3.5. Particle Size and Porosity

Porosity increases with the particle size, and this is important in balancing the surface area for growth of microorganisms. A large particle size increases the porosity and lowers the surface area to mass ratio. Thus, a value of 35%–50% porosity is best for composting [28].

3.6. Moisture Content

Moisture in faeces, urine or foam flush makes the nutrients physically and chemically accessible to microorganisms. A moisture content of 82% has been reported in faeces [33]. Several composting systems remove excess moisture since too much may create unwanted anaerobic conditions. However, if the moisture levels are below 40% the decomposition process slows down and activation water is needed [39]. According to several studies, a moisture content of 50%–60% is the optimum for proper composting [35,40], while an upper limit of 65% has also been proposed [35].

4. Microbial Risks of Faecal Matter Manipulation

The microbial risks of handling faecal matter have been assessed in a study that calculated the risks associated with the local handling and use of human faeces during the maintenance of composting toilets in Danish houses [24]. Manual emptying is more common for self-contained toilets in private households, while emptying of those with larger capacity may be performed with machinery and professional services. The human exposures assessed included accidental ingestion of a small amount of faeces or a mixture of soil and faeces while emptying the storage container. Inactivation of pathogens to acceptable levels was achieved after 12 months of storage [24]. Although the risks of transmission after one year of storage may still be high for some viruses, simple practices such as wearing gloves and face protection lower the risk significantly. The organisms included in the risk assessment were: *Salmonella*, enterohaemorrhagic *E. coli* (EHEC) (bacteria), Rotavirus, Hepatitis A (virus), *Giardia*, *Cryptosporidium* and *Ascaris* (parasites). The typical risks of emptying an infected container after a year are negligible for *Salmonella*, EHEC and *Giardia* while they are very low for Rotavirus, Hepatitis A, *Cryptosporidium* and *Ascaris*, respectively. The authors also calculated that the risk of infection from bacteria is low, regardless of the incidence rate in the population. Therefore, it is critical to keep the storage time to a minimum of 12 months to prevent any infection.

5. Commercial Dry Sanitation Systems Currently on the Market

Some of the most common commercially available dry sanitation systems for houses and public facilities are listed in Appendix A (Supplementary information), and they include self-contained or central, urine-diverting, electrical, and single or multi-chambered. Although these toilets are more expensive than flush toilets, the cost in the long term will be lower than the flushing ones [13] since water bills will be significantly lowered. However, to date, there is no standard guideline for composting toilets, which creates a lack of consistency in the presentation of toilet capacity. Some

factors to take into consideration when choosing the right dry sanitation system are the capacity, which is the number of uses/day, the availability of electricity, the population density, position of the composter (ground level or above) and climatic conditions, among others. It is also important to note that most of the models require frequent maintenance for their proper functioning. Adding bulking agents, spraying liquids and mixing the compost pile are critical to maintaining a good rate of decomposition.

Commercially Available Dry Sanitation Systems Intended for Remote Areas (National Parks, Rural Areas)

Central waterless toilets have a much larger tank and can be connected to multiple toilets. Vertical piping is needed to direct the faecal matter to the composting tank. They are designed for greater capacity systems and are usually required at public facilities such as national parks. Clearance of the underfloor is required for some of them, thus the compost treatment chamber is below the floor and separated from the toilet pedestal by a chute.

A few models were selected for further discussion because they are intended for remote areas such as national parks without access to water or electricity; they are also intended for large capacities (they have the largest composting tanks) and they require the least maintenance. Each of these models is described and compared in Appendix B (Supplementary information).

6. Future of Dry Sanitation Systems

Alternative options (not commercially available) include toilets using nanotechnology and solar power. In addition, the separation of urine to be used later as fertilizer has been advocated as a sustainable solution. Urine is nitrogen rich (75%–90% contributed by urea), and its phosphate and potassium compounds are readily water soluble and available for plants [41]; urine also has a low concentration of heavy metals compared to synthetic fertilizers [42]. Thus, its collection in diverting toilets represents a good alternative to conventional sanitation systems and it has been implemented in several developed and developing countries [43].

Some projects funded by the Bill and Melinda Gates foundation [42] include designs/prototypes such as a solar-powered toilet that generates hydrogen and electricity by CalTech, a toilet that produces biological charcoal, minerals and clean water, designed by Loughborough University, and a toilet that sanitizes faeces and urine while recovering resources and clean water, designed by the University of Toronto [44]. A toilet user interface designed by the Eawag has also been recognized.

A nanomembrane toilet was designed by researchers from Cranfield University and was also funded by the Bill and Melinda Gates Foundation in September 2012 [45]. This toilet is intended for urban poor areas because it requires maintenance only every six months. It uses thin nanofibres arranged in bundles inside the chamber that help move the water vapour through beads that condense the vapour into water. The solid waste is left to dry in a holding chamber until a technician removes it [45].

Thus, the future of dry sanitation systems appears promising. This review categorizes these systems and provides the latest commercially available models, with an emphasis on those with large capacities which require the least maintenance. We also aimed to describe the principal factors required to maintain an efficient composting process and, in general, to increase awareness of dry sanitation systems as a sustainable alternative for waste management, especially for remote and rural areas, as well as refugee shelters where water may be limited.

Supplementary Materials: The following are available at <http://www.mdpi.com/2071-1050/12/14/5812/s1>.

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Appendix A

Commercially available dry sanitation systems for houses and public facilities.

Appendix B

Commercially available dry sanitation systems intended for remote areas without access to water or electricity; they are also intended for large capacities.

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