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The Kailash Ecovillage project converting human excreta into organic foodstuffs and sanitized compost using new international building codes for compost toilet and urine diversion systems

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Abstract

Since March 2014, a sustainably focused community located on a 0.7 hectares site in Portland, Oregon, USA, has been undertaking an experimental composting toilet system modeled after the Water Efficiency and Sanitation Standard (WE-Stand) set out by the International Association of Plumbing and Mechanical Officials (IAPMO). This system collects urine and hot composts human excreta in a dry-composting toilet system for eventual use on the community's organic gardens. The system design reduces the need to access municipal water, sewer, and electrical infrastructure, enhancing emergency preparedness. It conserves an otherwise wasted nutrient flow, and safely produces a valuable compost. The system consists of urine collection vessels, multiple portable collection containers for excreta, toilet paper, and additive, and a compost processor. Urine diversion has allowed the community to reclaim nitrogen and other nutrients otherwise lost in conventional sewage systems, resulting in large savings of potable water and significant carbon sequestration via topsoil creation. Logs showed thermophilic compost temperatures. Compost and urine pathogen testing met American National Standards Institute and National Sanitation Foundation Standard 41 requirements.

Key words: ANSI, building code, cohousing, compost toilet, container-based sanitation, dry toilet, ecological sanitation, ecovillage, emergency preparedness, humanure, IAPMO, NSF-41, urine diversion, WE-stand

INTRODUCTION

We live in times of extreme sanitation inequality with 52% of all people in Asia having no access to basic sanitation and 95% of sewage (excrement mixed with potable water) in developing world cities being discharged untreated into rivers, lakes, and coastal areas where nutrient overload destroys and greatly reduces the potential of these ecosystems to support food security (Jewitt 2011).

Water-based sanitation (centralized sewer systems and decentralized septic tanks with drain fields) is the predominant paradigm in developed countries due to its user convenience and is often aspired to in developing countries. For example, from 1999–2012, more than 75% of new toilets installed in China were water flushed (Hu *et al.* 2016). However, these systems have many important shortcomings; they waste the valuable nutrient flow; are energy, capital, and potable water intensive, especially centralized systems with their extensive pipe network and often greatly backlogged service needs;

usually require functional electric power or water supply; are subject to failure when overloaded, as during rain events when combined with storm sewers; often discharge pollutants, such as pathogens, nitrogen, minerals, pharmaceuticals, and heavy metals, into the environment; can require large land areas to infiltrate the treated water into the environment, although most is discharged into surface waters (Brands 2014). For these reasons, many installations fail to meet minimum disposal standards and discharge polluted water into the surface environment (Bartram & Cairncross 2010). The US Environmental Protection Agency estimated capital investment needs at nearly $300 billion over the next two decades for U.S. wastewater infrastructure (Brands 2014). Anything that can be liquefied can be disposed of into sewers, such as heavy metals from industrial sources. For this reason, sewage can be highly toxic, even radioactive (Titley *et al.* 2000). Despite its shortcomings, water-based versus waterless sanitation typically costs an order of magnitude or greater to install and maintain (Huuhtanen & Laukkanen 2006). The city of Portland, Oregon, USA, where this project is located, has an estimated replacement sanitary sewer value of $8,784 per resident (Portland 2009), out of reach of most of the world's populace.

By contrast, composting toilet and urine diversion systems are a decentralized and waterless form of ecological sanitation that addresses these concerns. They work by turning ETPA (excreta, toilet paper, and high carbon additive) into humus, and urine into a treated fertilizer (Del Porto & Steinfeld 1999). They also can process normal household and garden compostables, helping to close local nutrient loops (Wielemaker *et al.* 2018). When well designed, these systems exploit the nitrogen, mineral, and organics nutrient flows; use no electrical power, drinking water, or fossil fuels; discharge no pollutants into the environment; have low capital and maintenance costs; are easy to maintain; and can reliably destroy pathogens (Winblad & Simpson-Hebert 2004; Jenkins 2019). Composting can also be a reliable way of breaking down excreted pharmaceutical residues (Butkovskyi *et al.* 2016).

Centralized sewer systems are also subject to catastrophic failure in a natural disaster (Larson 2018). The US Pacific Northwest region has a well-documented history of catastrophic seismic events that occur typically every 243 years. Scientists predict a 37% chance that an earthquake of magnitude 8–9 will occur in the next 50 years (Larson 2018). For example, in Oregon, site of this project and the expected Cascadia Subduction Zone earthquakes, 'Sanitary sewer systems are expected to fail and be inoperable for a period of months and up to a year … damage to between seventy five to one hundred percent of the wastewater system's physical structure is expected.' Oregon and New Zealand have studied container-based sanitation as a preparedness measure, planning for excreta to be segregated into urine and dry fecal-additive stores during the anticipated sewer failure, that can allow later composting and treatment of the materials so they can be recycled back to the environment. Haiti has already developed an ongoing container-based collection and composting system (Kramer *et al.* 2011). Catastrophic central sewage system failures have occurred in Haiti (2010), New Zealand (2010), and East Japan (2011) with recent earthquakes.

Since nutrients are lost in water-based systems, our agricultural systems have become more dependent on fossil-fuel-based fertilizers to grow our crops (Brands 2014). Because of their improved carbon performance, composting toilet systems can help to promote climate stability. Carbon sequestered in soil makes up the bulk of the Earth's non-oceanic carbon stores. So, the creation of compost from composted excreta can help replenish the earth's topsoil and be an important way to sequester carbon (Lal 2004).

In short, it is becoming increasingly apparent that the world must move closer to replacing the poorly performing water-based sanitation model with the ecological sanitation model of contain, sanitize, process and recycle. Some sanitation experts consider water-based sanitation an unsustainable anachronism and call for widespread adoption of water-free nutrient reuse paradigms (Winblad & Simpson-Hebert 2004).

The goal of this study was to explore a community's attempt to replace a portion of its conventional, water-based excreta sanitation system with a more sustainable, and more robust in emergencies, ecological sanitation ecosanitation system, including what barriers there might be to these changes.

CHOOSING AN ECOLOGICAL SANITATION SYSTEM

Overview of waterless excreta sanitation systems

There is a wide array of waterless sanitation system hardware designs that can be categorized based on excreta collection systems (Berger 2011; Anand & Apul 2014; Tilmans *et al.* 2015). Namely:

- Self-contained units that integrate ETPA collection and processor in a single unit, with continuous, ongoing, collection.
- Central units collect and pipe ETPA from physically remote toilets to a separate processor, in a continuous manner.
- Container-based sanitation collects ETPA in sealed containers for physical transport to the processor which uses batch processing.

All these systems may be further categorized by whether they separate urine at the collection point, whether a carbon-rich additive is added to excreta, and what kind of processing excreta undergoes (Berger 2011; Anand & Apul 2014). Processing can include thermophilic composting, or lower temperature (mesophilic) decomposition, also called moldering. To achieve thermophilic composting, an adequate compost chamber size, oxygen, and added high carbon substrates are required.

Self-contained units include pit privies, most commercially manufactured dry toilet systems, and several designs that allow construction on-site using commonly available materials like concrete, such as the clivus or double vault systems. Pit privies are simple unlined soil cavities that allow fecally contaminated urine to penetrate the environment. Carousel designs, with multiple vaults, are also self-contained units (Winblad & Simpson-Hebert 2004). Self-contained designs have the benefit of minimizing the handling of excreta, since it is deposited directly into the processor. These types of units use low temperature biological decomposition or desiccation. Thermophilic composting does not occur. For this reason, a long processing time, and critical check points are monitored to insure degradation of potential pathogens. This necessitates a voluminous processor, which can lead to difficult and expensive installation in conventional living spaces. Because at least some high carbon or other additive is required to facilitate decomposition and for odor control, this further reduces the space available for excreta storage. Commercially available units that have a large and adequate capacity can fail to allow easy access to the material being processed for optimal management, such as for bulk material balancing, to insure optimal carbon-nitrogen ratio, and leachate management. Improper processing conditions can then become anaerobic, creating odors, and their pathogen destruction is unreliable, despite meeting accepted certifications (Hill & Baldwin 2012; Hill *et al.* 2013). By contrast, ecosanitation systems achieving thermophilic composting have been found to reliably destroy resistant pathogens such as Ascaris (Berendes *et al.* 2015). One study suggested one cubic meter of composting volume is required to achieve thermophilic temperatures. This is much larger than most manufactured units (Jenkins 2018).

Central units separate the collection devices, termed toilets or *commodes*, from the excreta processing, but are physically connected by piping. If the commode is not located directly above, so the excreta can fall directly into the processor, it must be conveyed by foam, water micro-flush, or vacuum conveyance, allowing more flexible location of commodes but requiring more expensive and complex plumbing installation and electrical or piped water connection (Winblad & Simpson-Hebert 2004; Anand & Apul 2014). They offer the advantage of much greater flexibility in installation, since a typical commode takes up only a small footprint and size and hence can be located easily in most living spaces. However, extensive alteration of the living space may be required to install necessary piping. A separate large space is required to locate the processor.

Self-contained and central units both continuously collect and process the excreta.

Container-based sanitation systems have simpler collection designs, collecting ETPA in receptacles that are sealed and transported physically to the processor (Tilmans *et al.* 2015). There is no piping connection required. They also have the advantage of much greater flexibility in installation, since a typical commode takes up only a small footprint and size and hence can be located easily in most living spaces. A further advantage is that no plumbing, electrical, or ventilation connections are required, hence no alteration to a living space is required to install collection devices. Generally, container-based sanitation systems use a high carbon additive for effective odor control at the collection point. Because of their simplicity and the low cost of commodes, they are accessible to even the poorest populations. Multiple commodes can be serviced by a single processor located remotely and managed by specially trained workers, avoiding the necessity that each household site and manage its own processor or urine storage (Kramer *et al.* 2011; Jenkins 2012). Container-based sanitation systems use batch processing, whereby multiple containers are transferred into the compost processor at one time. ETPA can be considered the fuel for a heat-generating compost process. The main disadvantage of container-based collection systems is the extra ETPA transport step to the treatment areas and then into the processor.

Waterless sanitation can also be categorized based on the type of processing the ETPA undergoes. In some pit privies there is no further processing other than burial. Those that are emptied require processing elsewhere when filled. Self-contained and central units, which feed small quantities of excreta into the processor in a continuous fashion, and generally have small processors that are insufficient to insure thermophilic temperatures, process excreta by low temperature moldering or desiccation. Some self-contained designs employ energy intensive processing via incineration (Winblad & Simpson-Hebert 2004; Anand & Apul 2014). Those systems that employ thermophilic composting require significantly larger compost processors, and batch processing, to achieve their performance. A novel approach that uses earthworms to consume and digest the ETPA has been called vermicomposting (Hill & Baldwin 2012). This, however, is a misnomer, as no true composting occurs in these systems (Jenkins 2019). Because urine-derived ammonia is toxic to earthworms, they require urine diversion to perform adequately.

When container-based collection systems are combined with thermophilic compost processing we have a unique combination of simplicity of system design, low cost, flexibility of installation, and the possibility of processing by professionals. Processing is done in batches, in bins that allow complete access for ideal tuning of the process, resulting in thermophilic temperatures, which can significantly shorten the time needed to ensure pathogen destruction. Temperature-time parameters for reliable pathogen destruction (bacteria, viruses, helminths, and protozoa) are well known (Jenkins 2019).

The user sanitation experience is utlimately one of the most important features determining user acceptance (Hu *et al.* 2016; Cheng *et al.* 2018). All systems require brief visual and olfactory contact with excreta as it is collected. Olfactory contact can be prevented with negative pressure collection devices, but are rarely available, even with water-based systems. The simplicity of the water flush collection paradigm has gained it widespread acceptance. Pit privies can represent one of the worst user experiences: sustained visual and olfactory contact with excreta, and often vector infestation. Unless the excreta is removed for additional processing, an unpleasant and potentially dangerous user task, the nutrients may be wasted. Self-contained and central units, when well designed and maintained, can also offer a positive experience. The trade-off is the eventual task of partially decomposed excreta removal once the processor is filled. The user experience with container-based compost sanitation involves the periodic transport of the containers into the compost processor, although this latter task can be outsourced to third parties. The user interface with urine diversion can be unpleasant if unsealed, urine-exposed, surfaces are present and off-gassing ammonia.

Source separation of urine has numerous advantages (Huuhtanen & Laukkanen 2006; Kramer *et al.* 2011; Larson 2018). Urine makes up approximately 90% by weight and volume of human excreta and can be the source of most odors and usually few pathogens

(Winblad & Simpson-Hebert 2004). Urine is considered a high quality, complete, quick-acting, fertilizer, able to increase yields of vegetable and grain crops by a factor of from 2.2 (lettuce) to 4.9 times (barley). It is easy to apply, and guidelines are available for estimating application rates (Richert *et al.* 2010). It contains 90% of excreted nitrogen, 60% of phosphorus, and 50–80% of potassium, as well as other soluble nutrients, and is low in heavy metals, particularly when contrasted with synthetic mineral fertilizers, which are a chief source of this contaminant (Simha & Ganesapillai 2016). It requires no additives prior to transport. Separation is easy with inexpensive capped containers such as bottles (Steinfeld 2004). Collection is easily performed by men, women, children, transgender persons, and those with disabilities. Men can directly urinate into a capped container. Women may elect to use a simple *urethral extension device* which permits urination while standing. Alternately, a simple funnel can direct urine flow, while seated. Bottles are available in small sizes, permitting urine conservation while traveling for later deposition in a urine depot. They are easy to keep clean since all surfaces are directly accessible, unlike more complex piped systems such as urine diversion fixtures. Sealing urine contact surfaces, which can off gas ammonia, is the key to odor prevention. Surfaces in continuous contact with urine also tend to precipitate struvite, gradually occluding small diameter pipes (Winblad & Simpson-Hebert 2004). One approach to ecological sanitation is to focus on urine collection and recycling given its relative simplicity when compared to full excreta collection. In this approach the bulk of nutrients can still be reclaimed. Given human anatomy, collection with bottles can minimize fecal contamination (Simha & Ganesapillai 2016). Six months sequestration can be considered adequate sanitization for urine (Jönsson *et al.* 2004; Winblad & Simpson-Hebert 2004). Good practices also suggest no urine application less than 30 days from harvest. Although the issue of pharmaceutical residues has not been completely explored, and probably depends on each different drug, the risk from pooled, aged urine is considered low. Healthy soil is considered a bioactive environment to break down residues (Richert *et al.* 2010).

For simplicity, ease of implementation, extreme low cost, minimal odor, even compared to water based systems, and excellent performance, Kailash Ecovillage chose the container-based compost toilet and urine diversion sanitation paradigm.

The regulatory environment for waterless excreta sanitation systems in Oregon, USA, and Canada

Sanitation regulation in the USA is largely a matter of local regulation (city, county, state level). The American National Standards Institute (ANSI), has developed two standards for sanitation related technologies that may be adopted by individual jurisdictions.

NSF-41. Working with the National Sanitation Foundation (NSF) International, an independent, nonprofit, organization, ANSI developed ANSI/NSF-41: Non-Liquid Systems (NSF 2018). It is a standard allowing testing and certification for commercially available dry toilets. NSF-41 certification of commercially available devices insures:

- Compliance with construction, manuals, and performance standards,
- Six months of performance testing, both in the laboratory and in a mature field setting,
- The ‘humus’ product has <200 mpn E coli per gram and no objectional odor.

The cost of certification includes initial testing (once in facility and once for three mature in-field systems), as well as annual fees, and can be considerable. However, NSF-41 certified toilets are approved for installation in most US and Canadian jurisdictions. The first device was certified in 1989 (NSF 2018). Unfortunately, research in the field has shown disappointing results demonstrating excessive ammonia and waterlogged conditions, retarding pathogen destruction. In other words, NSF-41 certification does not ensure adequate processing (Hill & Baldwin 2012; Hill *et al.* 2013). NSF approved systems also allow discharge of unsanitized leachate into the environment, potentially contaminating ground water sources. (Buchanan 2015).

WE-Stand. Working with The International Association of Plumbing and Mechanical Officials (IAPMO), ANSI has developed standards, in the form of building codes, for the safe and efficient use of water in buildings, also called WE-Stand (IAPMO 2017). WE-Stand includes the first set of comprehensive codified requirements for the installation, safe use and maintenance of composting and urine diversion toilet design standards applicable to commercial and residential applications. IAPMO coordinates the development and adaptation of plumbing, mechanical, and other building codes to meet the specific needs of individual jurisdictions both in the United States and abroad. IAPMO has developed the Uniform Plumbing Code, another ANSI standard.

Some of the most important performance characteristics of this performance-based composting toilet and urine diversion building code design standard include:

- Systems shall be constructed of durable, non-corrosive, materials.
- An owner's manual shall present clear instructions for operation and maintenance, including microbial testing.
- Commode, processor, and urine diversion design and use shall minimize odors.
- There shall be no discharge of composting leachate into the environment.
- The composting processor shall be enclosed and adequately ventilated in a fashion that does not allow insects, birds, rodents, or rain to enter until the compost is finished at one year.
- Finished compost shall be used only for ornamentals and fruit bearing plants.
- Diverted urine will be retained for six months before usage and may be used for any garden areas, including food plants
- *E. coli* testing of initial compost output of a system $<$200 cfu/g.

It does not require thermophilic composting, but it does prevent contamination of the soil with pathogenic material such as leachate and compost less than one year old. Jurisdictional adoption of WE-Stand provides an opportunity for building code officials to approve performance-based composting toilet systems that have all these and other specified advantages. Until now, many container-based composting and urine diversion systems have not been permitted.

USA: Local Building Code officials, and in some cases, Health officials, supervise the installation of composting toilet systems in the United States (Del Porto & Steinfeld 1999; Jenkins 1999). Each local jurisdiction may have unique regulations, for example, approving NSF-41 certified devices or individual designs meeting WE-Stand building codes.

Canada: Canadian National Standards is a testing and certifying organization that has adopted NSF testing protocols.

State of Oregon: The state of Oregon, USA, has approved those manufactured composting toilets meeting NSF-41, as well as some individually approved designs. Oregon has not yet adopted WE-Stand.

Other American states: Each state, and sometimes smaller jurisdictions within states, such as counties or cities, may adopt its own regulations. Typically, NSF-41 certified devices are approved.

City of Portland: Portland follows the Uniform Plumbing Code and has approved NSF-41 certified devices as well as installations meeting WE-Stand design guidelines.

METHODS AND MATERIALS

A community composting toilet and urine diversion system

In 2014, Kailash Ecovillage, a sustainably focused, cohousing style, intentional community containing 34 residences, located on a 0.7 hectares urban site in Portland, Oregon, USA (latitude 45°29′31.39″N, longitude 122°37′31.02″W), elected to develop a prototype nutrient recycling system as part of its ecosanitation and emergency preparedness projects. For the multiple advantages of container-based compost and urine sequestration sanitation systems, and the local regulatory environment that recognizes WE-Stand, Kailash chose to develop an experimental composting toilet and urine diversion system based on the WE-Stand guidelines (Ersson 2019). Average annual temperatures at this location are 12.5 °C. Average annual rainfall, which occurs primarily in the non-summer months, is 0.93 m.

Garden description and land use

The ecovillage lies at the intersection of single and multifamily medium density residential areas. Besides the building and the parking areas, the entire ecovillage site is used for gardening and food cultivation. Land use differs from other local developments due to the ecovillage model.

A more traditional use of the northern half of the property was planned in 2009 for a suburban style 11-unit town home development. In that scenario, the largest use of the land would have been equal areas for pavement for an access street, parking, and housing, with a small space dedicated to ornamental plantings. However, this plan was dropped when it was incorporated into the ecovillage. The southern half of the property originally contained 42 personal vehicle parking spaces. However, 16 spaces have been removed and restored as garden area since the property transition in 2007. In most multifamily properties in the area residents are subscribed to regular city sanitary services to remove compostable biomass from the site and landscape maintenance of lawns and ornamental plantings is handled by hired crews. Most multifamily properties in this area have typically exported all roof and parking stormwater into the sanitary sewer.

In the Kailash project, all the original undeveloped land has been placed in cultivation. In addition, significant tarmac removal has increased garden space. All biomass recyclables such as food waste and plant refuse are retained on site. The property also receives regular deliveries of local ground tree waste. All gardening is performed by residents of the property, and some neighbors, using volunteer labor. All stormwater is retained on site by diverting to swales.

The gardens are comprised of approximately one quarter ornamental gardens; one quarter individually tended garden plots; and one half communally tended gardens, including 55 fruit trees, berry, grape, and mushroom gardens. The grape, raspberry, and blackberry vines plants total 206 m, 48 m, and 39 m in length, respectively. The biological recycling areas consist of two compost processors, one reserved for excreta composting and one reserved for kitchen scraps and garden compostables, the Urination Station and Urine Depot, and Wood Chip Depot, totaling 145 m^2, or 2% of the total surface area of the site. Each compost courtyard uses less than 0.6% of the garden space. Foot traffic on the site is on one-meter wide wood chip pathways. Extensive mulching of plantings with wood chips, in addition to compost production, has resulted in development of new topsoil averaging 15 cm in depth over the entire garden site since 2007. Mulched areas are colonized with wood-digesting edible mushroom species. See Figure 1.

How the system works

Residents choosing to participate in this project contact the Humanure Team to declare their interest in either collecting their combined excreta, or urine for recycling. If they only want to collect urine, they are instructed in how to collect and deposit their urine into the community storage tanks. If they also want to host a commode to collect both solid and liquid excreta, they will be issued one of the community's compost commodes and receive instruction on how to properly manage it, e.g., for strict odor control. They are responsible for transporting their containers of ETPA (excreta, toilet paper, and high carbon additive) to the compost processor. The team is charged with periodically emptying batches of containers into the compost processor, recycling accumulating leachate, cleaning and sanitizing the containers for reuse, and record keeping. The team also prepares clean containers

Figure 1 | (a) The ecovillage site map, showing the different land uses. Gardens are shown in greens, swales in blue, parking in tan, bio-recycling areas in orange, and buildings in grey. (b) The front gardens and swale area. (c) Fruit and (d) vegetable harvests.

filled with additive material consisting of finely sifted ground trees, harvested from the urban biomass stream. These readied containers, and a small number of empty containers, are kept in a designated location. One expert resident oversees testing all the compost and urine before use. Resident participation in this project is optional, and all residents have access to flush toilets in their residences. Equal numbers of residents participate in urine collection and full combined excreta recycling. Residents receive credit for an hour per month specified volunteer time in this project.

Raw materials

The composting toilet and urine diversion system consists of the following components: ten portable commodes, a depot for receiving unprocessed ground trees called a wood chip depot, a depot for storage of empty containers and containers filled with prepared additive, an outdoor compost processor, and an outdoor urine collection depot, called the Urination Station. These components are described in detail below.

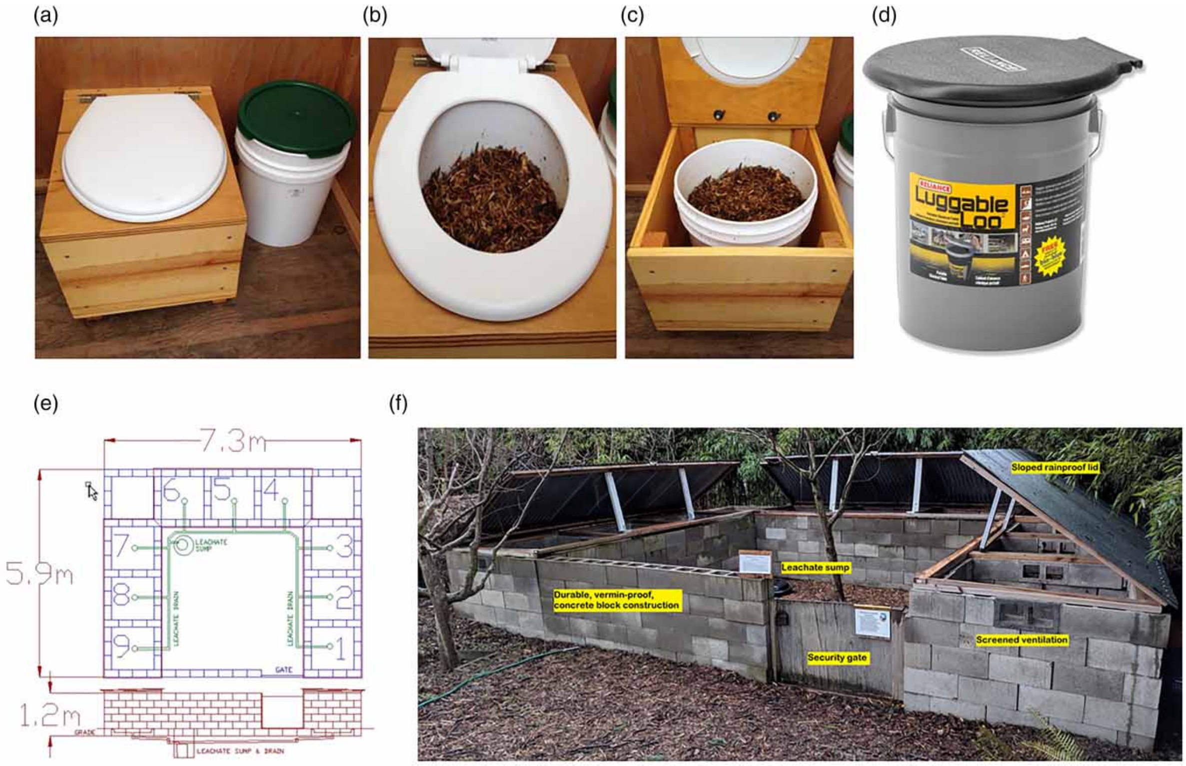

Figure 2 | (a) Compost commode and additive. (b) Collection container inside. (c) Full container. (d) Commercially available portable commode, $20, at camping store (e) Compost processor schematic. (f) Compost processor.

Commode

Each commode is a simple wooden cube-shaped cabinet designed to hold a container, such as a 19 litre receptacle, which is the ETPA collecting device. The commode cabinet and adjacent additive container require only a very small footprint on a floor and can be installed without electricity, water, or a plumbing connection. Several commodes, located in residences, can be accommodated by a single compost processor system. See Figure 2 and Table 1. Inexpensive plastic seats with hinged lids that snap onto a receptacle, available from camping supply stores, can also serve as a commode.

Table 1 | Materials list, commode, compost processor, urine collection devices, and urine depot

Commode	**Design inspired by the Joseph Jenkins Loveable Loo™**
Cabinet	Sealed fir, pine, or other common woods capable of holding a 19 litres container; dimensions: 38 cm wide, 51 cm deep, 38 cm tall If the cabinet is sealed, negative air pressure devices can be installed for source prevention of all odors
Lid	Plywood
Toilet seat	Standard, compression molded plastic; height from floor: 41 cm
Container	19 litres with lid (excreta collection device)
Cost	Materials: about $20, labor $30
Features, recommendations	• Waterproof, sealed wood • Easy to install, permanent, odor free • No electricity, water, plumbing connections required • Inexpensive

(*Continued.*)

Table 1 | Continued

Commode	Design inspired by the Joseph Jenkins Loveable Loo™
Optional	Negative pressure ventilation fan to prevent odors during use, vents to outside the living space
Compost processor	
Bins (nine count, three modules)	• Dimensions ○ Exterior 7.3 × 5.9 metres ○ Bin interior dimensions 1.2 × 1.2 × 1.1 metres ○ Bin capacity: 1.66 cubic metres • Walls ○ Durable, low-cost, 20 × 20 × 40 cm concrete blocks (insulation) ○ Vermin proof ○ Wooden sill plate for roof support (located on top of walls) • Bottom ○ Sloped concrete pad ▪ 10 cm above-pad perimeter lip ○ Waterproof ○ Center drain grate (leachate collection) • Roof assembly (sloped) ○ Corrugated, galvanized steel ○ Rain accumulation prevention ○ Vermin mitigation ○ Hinged ○ 3-bin module shares a common roof
Sump area (plumbing)	• Leachate collection includes drain grate, sump enclosure, lid • 5 cm internal diameter ABS piping and fittings with 2% slope • Contamination prevention of local soil and groundwater
Ventilation	• Wire mesh screen air vent (hardware cloth) • Vermin and insect management • 902 cm^2 per bin
Security	Gated courtyard (hinged and latched)
Cost	Materials: $2400
Features, recommendations	Nine (9) bin system accommodates 19 full-time adults
Urine collection devices	
Bottles	• Available in many sizes and types ○ As virgin containers, purposed for urine ○ As recycled beverage containers ○ Portable, can fit in large pocket ○ Personal ○ Easily sanitized ○ Require ability to cap and seal tightly ○ Rinse 3 times with 5–10 ml water and empty into collection container to clean, reduce odors and struvite formation
Urethral extension device (optional)	• Multiple models commercially available • Personal hygiene device, cost about $12 • Portable, personal, easily sanitized • Can also use a simple funnel
Urine depot	
Urination station	Consists of a small shelter to house a combined excreta commode and wall-mounted dry urinal and surrounded by urine sequestration tanks. Used as a toilet by visitors and gardeners.
Features, recommendations	IBC (Intermediate Bulk Container) tanks used for urine sequestration • Reusable • Constructed of high-density polyethylene (HDPE) • Ideal for storing liquids • Holds the same capacity as five 210 litre drums, in less space

(*Continued.*)

Table 1 | Continued

Commode	**Design inspired by the Joseph Jenkins Loveable Loo™**
Cost	• One (1) 210 litre barrel $5 • Three (3) 1,040 litre IBC tanks (urine sequestration), $100 each • Wall mounted dry urinal $502 • 2 m of 10 cm ABS conveyance pipe, plus fittings, $30

Commode use

A 5 cm layer of additive is placed at the bottom of the empty commode receptacle prior to adding excreta. Each excreta deposit is then carefully covered with additive and pressed flat. This effectively prevents all odors as wood chips are an effective biofilter (Chen *et al.* 2009). Once the container is full, and a lid is fastened, it is transported to the compost processor. Toilet paper or small amounts of water used for anal cleansing can be added. If the commode is optionally fitted to generate a negative pressure at the toilet seat, the ventilation fan is activated prior to use. This can effectively prevent egress of any odors during use from entering the space outside the cabinet.

Additive

The additive consists of sifted, finely ground wood and leaves, recycled from local tree service companies. It covers all ETPA deposits both in the collection receptacle and in the compost bins and serves as an effective barrier for all odors (Chen *et al.* 2009). Except for coniferous based species, which have a pleasant odor, these materials are generally odorless or just have wood or foliage odors. Sawdust, shredded paper or leaves, and other agricultural waste products like bagasse, cereal hulls, or chopped straw, can also be used and are generally odorless (Jenkins 2019).

Compost processor

The compost processor consists of several large bins, arranged in modules of three, which share a common roof. The walls are constructed of durable but unmortared concrete blocks and the bottom is constructed of a lipped concrete pad sloped toward a drain in the center to collect any liquid resulting from composting, called leachate. Ventilation openings are screened with wire mesh to prevent insects, birds, and rodents from entering the compost processor. Three modules are arranged in a gated courtyard. All the bins have a sloped roof that prevents rain from entering the compost processor and keeps out vermin. Leachate from each bin collects in a sump area and is recycled back into the compost processor, by simply adding it with each new batch of ETPA. This helps maintain the proper moisture level for healthy composting, as well as preventing potential pathogens from entering local soil and ground water. See Figure 2 and Table 1.

Composting process

Every two to four weeks, containers of ETPA are added to the compost bins in batches, along with accumulated leachate, and the water used to rinse the containers, and then covered with a 10 cm layer of additive to effectively prevent all odors (Chen *et al.* 2009). A similar layer of additive is used around the perimeter and on the bottom of the bins to insulate the ETPA while composting. ETPA is approximately 25% excreta by volume. Once a bin is full, its completion date is marked on the front of the bin. After one year has passed, the compost is tested for pathogens and is ready to distribute to the gardens.

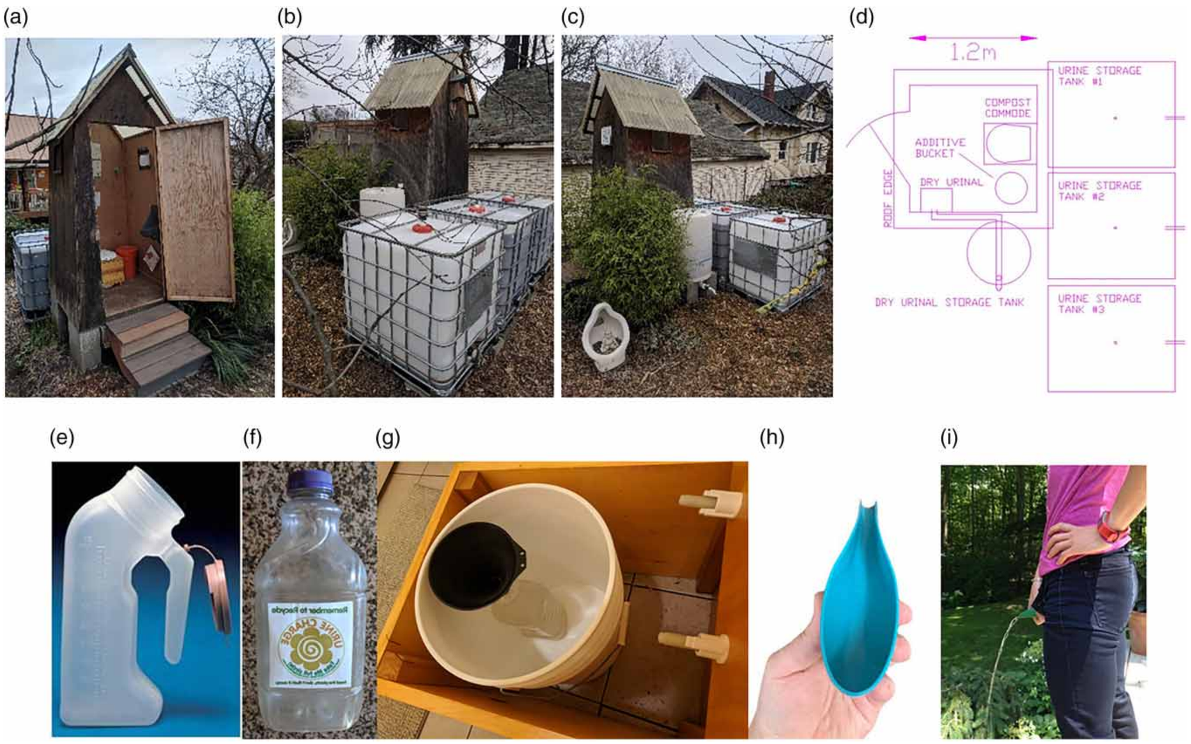

Figure 3 | (a) The interior of the 'Urination Station' has a dry urinal and compost commode. (b) Photo of the rear showing three long-term urine storage tanks. The short-term storage barrel for the dry urinal is shown in (c). (d) The plan of the Urination Station shows the inside of the 1.2 m × 1.2 m structure with location of dry urinal and commode and the outdoor tanks. (e, f) Urine is easily collected in containers and bottles, sometimes using funnels (g) or personal hygiene devices (h) like the P-Style, which permits women to urinate while standing (i).

Urine collection and treatment

Urine is collected as part of ETPA in the usual fashion in commodes, or in bottles in residential spaces, or by visitors using a waterless, wall mounted, urinal in a small outdoor structure adjacent to the urine storage depot. See Figure 3. For simplicity, low cost, odor prevention, and flexibility, no urine diverting toilet fixtures are used.

Performance monitoring

Performance logs were maintained for the 56-month period from 8 March 2014 through 8 November 2018 and recorded quantity and dates of ETPA, leachate, and rinsate processed at each filling session. Logs also recorded the dates each compost bin was filled and when they matured one year later. Similarly, the logs recorded the fill and six-month maturation dates of each urine sequestration tank, and the dates and quantities of urine distributed to the gardens.

Compost temperatures were monitored for several bins daily, after each batch of compost was added to a bin, using a 50 cm long General Tools PT2020G-220 Analog Soil and Composting Dial Thermometer.

Each tank of urine was tested for pH using Labrat Litmus pH Test Strips, Universal Application (pH 1–14) by drawing a 10 ml sample from the top tank opening after 30 seconds of vigorous tank stirring.

Compost samples of bins 1, 2, and 3 were tested on 1 April 2019 for moisture by subtracting dried weight from fresh weight samples of approximately 250 g after drying in a 77 °C oven. The samples were taken from 3 representative points in the bins 20 cm from the bin perimeter and thoroughly mixed together.

Additionally, each compost bin and each urine tank were sampled and tested for pathogens prior to distribution to the gardens. Compost bins were tested for fecal coliforms at their one-year maturation date according to National Sanitation Foundation (NSF) guidelines, Standard 41, Sections 12.1–12. 3. For each bin tested, 5 samples were collected. Samples weighed 10 grams each. Sample collection points were evenly distributed from throughout the bin and were representative of the contents of the entire bin. The 5 samples were thoroughly mixed together prior to testing, then tested using Coliscan Easygel test kits at the manufacturer's recommended dilution of 100×. Samples were incubated at 40–44 °C for 48 hours, per manufacturer's recommendation. Urine samples were also tested using a 10 ml sample taken from the top tank opening after 30 seconds of vigorous tank stirring.

An April 2019 email survey of all current users asked questions about system performance, aesthetics, and suggestions for improvement. Each free format response was recorded in a survey document. The survey in particular asked users to comment on ease of use and whether odors were a problem.

RESULTS

Product

Logs from the 1660 days (56 months) from March 8, 2014 through November 8, 2018, show quantities of ETPA (excreta, toilet paper, and high carbon additive), leachate, rinsate, urine, and compost produced. The bins have an actual ETPA capacity of up to 120 containers per bin, but a substantial amount of garden compost, as well as cover material, was also processed in the bins. The actual amount of compost produced in the processor is about half of that added as raw material. Moisture testing of three samples of finished excreta compost showed an average moisture content of 33%. See Table 2.

Compost temperature monitoring

Careful compost temperature monitoring occurred daily from 27 June 2015 through 27 December 2015. Temperatures were taken at the center of the bin, 10 cm from the edge, and the edge of the bin, at the depth of the compost thermometer. Three periods of daily temperatures following adding batches of ETPA showed a consistent and rapid rise in center of compost temperatures to at least 63 °C within four days and continuing as high as 52 °C at the end of each two-week period. This sudden increase was followed by every addition of fresh ETPA. Weekly monitoring also occurred

Table 2 | Production and frequency of bins, ETPA, leachate, rinsate, urine, compost (8 Mar 2014–8 Nov 2018)

Item	Quantity	Frequency
Bins	23 bins, averaging 84 ETPA containers per bin	72 days per bin
ETPA	1922 containers (29,102 litres)	18.2 litres per day
Leachate	2491 litres	1.8 litres per day
Rinsate	1643 litres	0.9 litres per day
Urine	9002 litres	5.3 litres per day, 44 litres per week
Compost	19 cubic metres	4.3 cubic meters per year

during 9- and 13-week periods showing thermophilic composting (above approximately 41 °C) was reliably achieved in the entire compost mass.

For example, the daily temperature logs for Bin #6, monitored after the last batch of ETPA was added, and continuing for 9 weeks, shows rapid onset of and sustained high pathogen killing temperatures. See Table 3 for recorded temperatures from 25 Oct through 27 Dec in the center of the bin, 10 cm from the perimeter, and the perimeter. Even 10 cm from the bin perimeter, the extent of the ETPA mass being composted, temperatures above 40 °C were sustained for 28 days, and above 50 °C were sustained for 10 days. Temperatures for this period are graphed in Figure 4 after a last batch of ETPA was added to the bin on 25 Oct. 50 °C is the temperature reported to destroy all pathogens in 24 hours (Jenkins 2019).

Pathogen testing

Compost pathogen testing for fecal coliforms has demonstrated a high-quality product, exceeding the US Environmental Protection Agency (USEPA) standards for Class A biosolids (<1,000 fecal coliform cfu/g) for compost safety, permitting application on any crops (EPA 1994; Crohn *et al.* 2000). According to the Environmental Protection Agency, 'In general, exceptional quality (Class A) biosolids used in small quantities by the general public have no buffer requirements, crop type, crop harvesting or site access restrictions' (Omick 2013). The only time significant fecal coliforms have been detected was when one bin was tested after leaving it open for several months while emptying. At that time, evidence of mice excavation was noted in the compost prior to testing. This batch likely contained murine fecal material. See Table 4.

Urine testing also showed fewer than 1 fecal coliforms and a pH between 9.5 and 10. The first tank was tested on 1 Feb 2019 as the urine diversion portion of the project began later than the combined excreta portion.

Use of excreta derived compost and urine on ecovillage crops

WE-Stand regulations restrict compost use to ornamental and fruit bearing crops. In this project, excreta compost was used primarily to enrich ornamental plantings, although a moderate amount was also used on fruit trees and cane berries. Treated urine may be used on any crops by first distributing it to the soil at the base of growing plants and then applying brief overhead irrigation to wash urine from foliage and the surface soil, thereby preventing any lingering odors. This serves to also dilute the urine. Prior to implementation of this ecosanitation project, plantings were fertilized with imported nutrients, such as guano, seed meal, and alfalfa meal. Once the excreta derived fertilizers became available, no further importation of fertilizers was required.

Community experience

The community's experience with this system has been very positive in benefiting from a new and sustainable nutrient flow, previously wasted. The compost produced by the system has significantly enhanced soil fertility and tilth. The community is now self-sufficient in nitrogen and other important nutrients and enjoys enhanced emergency preparedness considering the region's anticipated severe earthquakes.

Aesthetics

The only time odors are potentially present in this system is during commode use but before excreta is covered; during ETPA batch transfer to the compost processor but before covering

Table 3 | Bin #6 – Compost temperatures, taken at center of bin, 10 cm from outside bin edge, and at bin edge; daily and weekly logs (°C)

Daily log

Days after filling	**Before topping**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Center	55	31	48	68	74	75	73	71	69	67	66	65	65	65	64
10 cm inside perimeter	41	48	54	57	57	56	55	54	54	53	52	51	50	50	49
Perimeter	32	25	27	28	28	29	28	28	28	28	27	27	26	26	26
Date	25 Oct 2015	26	27	28	29	30	31	1 Nov	2	3	4	5	6	7	8

Weekly log

Week	**0**	**Peak (Day 5)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9 Final check**
Center	55	75	71	64	59	57	54	42	36	21	16
10 cm inside perimeter	42	56	54	49	45	41	33	23	22	17	13
Perimeter	33	29	28	26	22	18	13	9	9	7	4
Date	25 Oct 2015	29 Oct	1 Nov	8 Nov	15 Nov	22 Nov	29 Nov	6 Dec	13 Dec	20 Dec	27 Dec

These temperatures were taken after the last batch of ETPA.

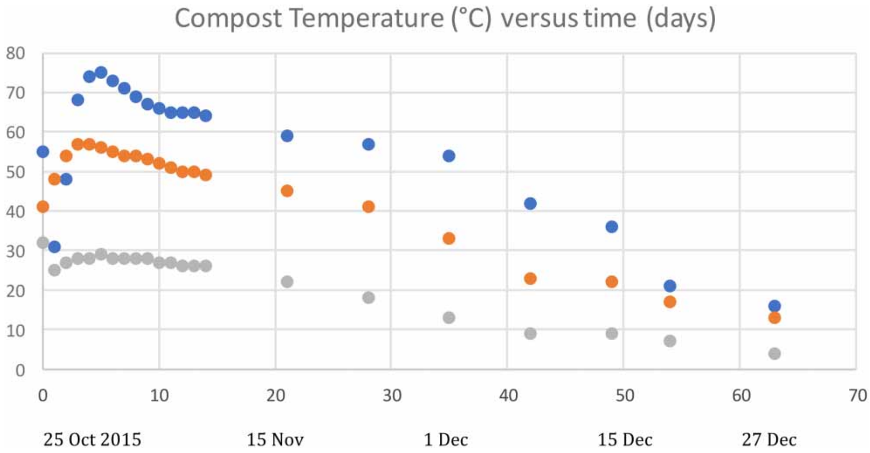

Figure 4 | Compost temperature (°C) versus time (days). This graph shows the temperature of Bin #6, versus time, recorded daily for two weeks, then weekly, up to 9 weeks from the *last* batch of added ETPA, demonstrating thermophilic temperatures were achieved from the center of the bin (blue) to 10 cm inside the bin perimeter (orange). Gray represents the bin perimeter, or ambient, temperature. Day 0: 25 October 2015; Day 63: 27 December 2015.

Table 4 | Pathogen testing of finished compost before emptying

Bin #	Date bin completed	Pathogens detected (fecal coliforms) Colony forming units per gram compost	Test date
9	3 May 2014	< 1	25 May 2015
8	27 Jul 2014	< 1	28 Jun 2015
7	12 Oct 2014	< 1	28 Jun 2015
3	22 Aug 2015	< 1	5 Oct 2015
2	22 Aug 2015	< 1	5 Oct 2015
1	22 Aug 2015	< 1	5 Oct 2015
4	22 Aug 2015	2100	31 May 2016
5	22 Aug 2015	< 1	31 May 2016
6	15 Oct 2015	< 1	31 May 2016
1	24 Jan 2016	< 1	5 May 2017
2	12 Mar 2016	< 1	5 May 2017
3	7 May 2016	< 1	5 May 2017
4	11 Jul 2016	< 1	5 May 2017
5	29 Jul 2016	< 1	5 May 2017
6	25 Sep 2016	< 1	5 May 2017
7	20 Jan 2017	< 1	15 Dec 2017
8	20 Jan 2017	20	15 Dec 2017
9	31 Mar 2017	< 1	15 Dec 2017
1	24 June 2017	< 1	17 Dec 2018
2	27 Sep 2017	< 1	4 Jan 2019
3	17 Apr 2018	< 1	4 Jan 2019
4	15 May 2018		
5	8 Nov 2018		
6	18 Jan 2019		

new batches; and during aged urine application to the soil. In this medium density urban location, there have never been neighbor complaints registered about performance or aesthetics. An email survey of all current users in April 2019 showed 11 persons recycling their combined excreta and

11 more recycling only their urine, not including occasional guests. The free form survey results showed great satisfaction with the system, complementing its ease of use, simplicity, and effectiveness. No odor complaints were registered. In fact, several users remarked on the lack of odors. Kailash has two commodes that use fans to generate negative pressure which prevents any odor from entering the commode space. Otherwise, there may be odor during use, as with water closets.

Water savings from implementing the system

Data from this project demonstrates about 38 litres of urine per week are diverted from toilet flushing. Assuming typical urination volume of 0.3 litres, residents are thereby avoiding 127 flushes per week. At 5.7 litres per liquid flush, this comes out to about 723 litres of water conserved per week, or 37,596 litres per year.

Assuming 70 solid flushes per week are being avoided at 7.6 litres per solid flush, this comes out to ~530 litres per week, or 27,558 litres of water conserved per year.

Financial costs

The Kailash Ecovillage excreta recycling project capital costs were about $4,000: $2500 for the compost processor, $500 for the urination station, $300 for three urine sequestration tanks, and $500 for 10 compost commodes. Divided by approximately 20 users, this comes to less than $200 per user. Although approximately two to three person-hours per month was required to perform additive preparation and composting tasks, the project is staffed with all volunteer labor, so no costs were incurred in maintenance.

Carbon sequestration

Composting results in a large amount of carbon sequestered in the beneficial compost product. This system has produced 19 cubic metres of compost in its first four years, eight months, for about 4.3 cubic metres per year.

DISCUSSION

Multiple implementations of ecological sanitation have been described, mostly in the developing world and in Europe.

For example, Winblad and Simpson-Hebert list the following implementations, serving thousands of persons, and their excreta recycling paradigm (Winblad & Simpson-Hebert 2004):

- Asia (China: household double vault, or vaults with removable containers, with PVC chute from upper floors and urine diversion; Vietnam: household level concrete double vault; Japan: single vault with urine diversion; Ladakh, India: single vault systems using soil; Kerala, India: urine diverting, double vault systems with evapo-transpiration for anal wash water; Sri Lanka: double vault with urine diversion and anal wash water diverted to evapo-transpiration beds; Palestine: urine diversion with fecal collection in multiple plastic containers and anal wash and grey water collected in septic tanks; Micronesia: concrete double vault systems with evapo-transpiration beds; Yemen: multi-storey, long drop, single vault dehydrating systems with evaporation of urine and anal wash water)
- Europe (Norway: carousel four-vault manufactured systems with either urine diverting commodes or with evapo-transpiration of leachate; Sweden: single vault manufactured systems, urine diverting

systems with 80 litre plastic fecal containers, small-water-flush single vault communal systems with flush and greywater septic systems; Germany: a vacuum-water-flush with biogas system)

- North America (Mexico: single and double solar heated manufactured vault systems; El Salvador: double vault dehydrating systems; Guatemala: urine diverting double vault systems with urine diversion)
- Africa (Zimbabwe: single and double vault systems using soil, and container-based systems using soil).

All these systems used low temperature desiccation or decomposition, although mention was made of possible additional secondary processing. Except for the manufactured units in Sweden, Norway, and Mexico, all appeared to be custom built, concrete, designs. None of the systems used thermophilic composting to address pathogens and sanitization performance was not documented. It was unclear where or how the recycled nutrients were used, and whether timed sequestration was used for urine treatment.

Werner discusses 4 holistic ecological sanitation systems: two systems in India (one that diverts urine for fertilizer, one that uses anaerobic decomposition to produce useable gas), one in Syria using constructed wetlands to treat water-based sewage, and one in Germany that collects urine for processing into a fertilizer (Werner *et al.* 2009). All these systems used low temperature decomposition. It was not described where or how the nutrients were recycled or if pathogens such as Ascaris was tested.

Simha discusses ecosan implementations in Europe (Germany, Sweden, Netherlands, Denmark), Asia (India, China, Nepal, Philippines, Pakistan, Indonesia, Turkey), and Africa (Malawi, Burkina Faso, Kenya, Tanzania, Mozambique, South Africa, Uganda) (Simha & Ganesapillai 2016).

Jönsson discusses ecosan implementations in Zimbabwe, Ethiopia, Mozambique, Benin, South Africa, Sweden, and Germany (Jönsson *et al.* 2004). Details of the individual designs, numbers of persons served, and whether low or high temperature processing was used was not described, nor where or how the nutrients were recycled, or if pathogens such as Ascaris were tested.

Cheng, Hu and others describe the ambitious Chinese program to install improved sanitation in both rural and urban Chinese settings, also known as the 'Toilet Revolution', with the goal of 'turning waste into value' as well as preventing pollution of the environment. In rural settings, the coverage of sanitary toilets has increased from 7.5% in 1993 to 78.5% in 2015. This is a remarkable achievement, with installations reportedly numbering in the tens of millions or more units annually. However, water-based sanitation comprises most new installations and the predominant dry systems used have been low temperature devices (dual pit, dual urn, urine diverting dehydration, and biogas linked). Also notable is that some initially dry systems subsequently were replaced with water-based systems due to user unacceptability. It is unclear from their descriptions what processing of excreta is ultimately used, and whether sanitization was insured, as some systems appear primarily to be collection devices with anticipated periodic emptying and final processing off site (Hu *et al.* 2016; Cheng *et al.* 2018). No description of final processing and use of excreta was described, although it was presumably for agricultural purposes.

Hu *et al.* also described four additional systems in Bolivia, India, Germany, and Changshu, China in more detail (Hu *et al.* 2016). The German model was a vacuum-assisted, water-based system for combined excreta using anaerobic digestion for biogas and a constructed wetland. The digestate went to a sludge treatment plant. The Changshu system also uses a vacuum-assisted water-based system for combined excreta, 'fermentation', composting of the solids, and agricultural irrigation of the supernatant. The Bolivian and Indian systems used urine diversion and purported to 'compost' feces with subsequent use as a fertilizer. Actually, red worms consumed the feces in Bolivia. In both systems anal cleansing water is used for irrigation of a nonedible wetland. No mention was made of pathogen testing of any of these non-thermophilic systems.

One wonders why thermophilic composting technology has not been used more widely, especially in China, as this would require little more than incorporating adequate quantities of appropriate high carbon additives such as rice hulls, or other widely available agricultural residues, into the collection process, and could also serve to eliminate odors, the most common complaint about these alternative toilets.

The problem with all widely used low temperature ecological sanitation paradigms is the concern for soil transmitted helminths (STH), including Ascaris, which are endemic in many global settings. Low temperature decomposition cannot be considered a reliable sanitization process. Ascaris can survive 2 years in soil and up to 4 years at 0 °C (Jenkins 2019). Even low temperature anerobic digestion for biogas production cannot be considered a reliable method of sanitizing human excreta, with multiple helminth species, including Ascaris, noted in unpasteurized bioslurry digestate samples (Poudel *et al.* 2009). By contrast, high heat and moisture are known to quickly inactivate Ascaris, so thermophilic composting can be an effective and proven way to sanitize feces (Gibson 2014).

Jenkins discusses community ‘humanure’ (container-based thermophilic compost sanitation) project locations serving hundreds of persons in North America (North Dakota, Haiti, Nicaragua), South America (Columbia), Africa (Tanzania, Uganda, Kenya), and Asia (Mongolia). None of these low-cost systems divert urine. Although these systems use high temperature thermophilic composting to sanitize feces (Jenkins 2012, 2018, 2019), because the bins are not lined on the bottom to prevent leachate loss into the environment, they do not meet WE-Stand guidelines. Kramer discusses a similar project in Haiti serving hundreds of persons (Kramer *et al.* 2011). Studies have confirmed the reliable inactivation of Ascaris transmission in Haiti with thermophilic composting (Berendes *et al.* 2015). The compost produced in these settings appears to have been recycled locally or sold as an agricultural supplement.

Richert *et al.* discuss ecosanitation systems using urine diversion to grow cereals (northern Europe and India), vegetables (South, East, and Western Africa, northern Europe, and central America), and fruit (India) and discusses nutrients, human production, chemical pollutants and salinization, economic value, application guidelines, storage, sanitization, application techniques and how to develop local guidelines (Richert *et al.* 2010).

Besides the pathogen issue, other potential ecological sanitation concerns needing more research include increased soil sodium concentrations from using urine, ammonia released to the atmosphere, potentially contributing to greenhouse gases, pharmaceutical residues in urine, and the need for transport of excreta recycled products to agricultural areas (Simha & Ganesapillai 2016).

These studies suggest two ecological sanitation paradigms: urine diversion with sanitization via sequestration, and fecal treatment that includes eventual thermophilic composting. For this reason, container-based compost sanitation, with or without urine diversion, deserves wider implementation, and is provided for in WE-Stand.

The world faces enormous challenges in global sanitation, water shortages, pollution from water-based sanitation systems, food insecurity, and global warming due to over reliance on fossil fuels which is partly attributable to broken sanitation and agricultural systems (Winblad & Simpson-Hebert 2004). The fundamental flaw in water-based systems is the lack of appreciation for the nutrient potential and potentially ecologically restorative nature of human excreta. What is needed is a change to a ‘contain, sanitize and recycle’ paradigm meeting the following criteria: disease prevention, environment protection, nutrient recycling, affordability, acceptability, and simplicity. These are the hallmarks of ecological sanitation. Unfortunately, the sanitation crisis does not involve only developing countries. Modern sewage systems widespread in the developed world suffer from some of the same flaws as those in developing countries. As Winblad and Simpson-Hebert state in envisioning an unfolding healthier world paradigm of ecological sanitation, ‘we see existing cities served by old and decaying sewerage systems being retrofitted with ecological sanitation systems’ (Winblad & Simpson-Hebert 2004).

The Kailash Ecovillage ecological sanitation project is one model that demonstrates the ease and low cost with which ecosanitation can be integrated, even in a developed world setting well served by water-based sanitation, with a local, community-based, agricultural system for organic food production with good user acceptance as well as performance. Outstanding features of this project include: local reuse of recycled nutrients, avoiding the need for transport, community operated and managed sanitation system, high user acceptability, even for those used to water-based sanitation, thermophilic composting to address pathogen treatment and pharmaceutical concerns in excreta compost, and low cost to implement a parallel sanitation system that can serve for emergency preparedness. The Kailash project appears to be the first published implementation of a community compost toilet and urine diversion system using the new WE-Stand building codes.

It is a paradigm that merits consideration in any urban setting with a motivated community, adequate garden space (or a way of exporting the nutrients), and an appropriate regulatory environment, such as those using WE-Stand. Ecovillages, with a shared resident focus on sustainable living, are ideal locations. If earth-based garden space is not available, a similar project could be attempted in a denser setting using a rooftop gardening approach (Wielemaker *et al.* 2018). Or, excess nutrients could be exported. With indoor composting, even less garden space would be necessary. Lack of any of these necessary conditions could be a hurdle to implementation.

Now that the project is proven, it could be expanded to serve the entire ecovillage community of 55 residents. Each nine-bin processor is rated for 19 full time adults and takes up 0.6% of garden space. Therefore, adding two more sets of processors could accommodate all 55 ecovillage residents, with an increase of recycling area to just over 3% from the current 2%. This could be accomplished with replacement of all ecovillage flush toilets with compost commodes, leaving the water-based sanitation limited to greywater that could be processed also on site, for example using constructed wetlands.

CONCLUSIONS

Kailash Ecovillage's community compost toilet and urine diversion system has demonstrated how human excreta can be successfully rebranded as a 'resource' instead of 'waste', even in a developed world, urban, setting. Excreta, when managed properly, is a sustainable resource ideally used to recycle nutrients and carbon into a safe and beneficial soil amendment and garden fertilizer that requires minimal system inputs. Currently, however, in both developing and developed countries, excreta is rarely considered a resource and its misuse and wastage continues to contribute to great environmental damage. The development of the performance-based IAPMO WE-Stand guidelines can serve as an important milestone and guide for more widespread recycling of this resource and consequent potable water savings, nutrient recycling, carbon sequestration, and enhanced emergency preparedness.

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