This is a peer-reviewed, accepted author manuscript of the following article: Somorin, T. O. (2020). Valorisation of human excreta for recovery of energy and high-value products: a mini-review. In M. O. Daramola, & A. O. Ayeni (Eds.), *Valorization of Biomass to Value-Added Commodities: Current Trends, Challenges, and Future Prospects* (pp. 341-370). (Green Energy and Technology). Springer. https://doi.org/10.1007/978-3-030-38032-8_17

Table of Contents

Valorisation of human excreta for recovery of energy and high-value products: a mini-review

Tosin O. Somorin[1]

Abstract

The current approach to managing waste is one of the major reasons for ecosystem imbalances. In many parts of the world, human excreta are indiscriminately dumped in the environment, leading to the entry of high concentrations of nutrients and pathogens. In urban sanitary systems, nutrients are often not recovered, but large amounts of natural resources (e.g. water) are used for treating wastes at the expense of the environment. These practices are unsuitable and pose risks to human health and the environment, as such current efforts are geared towards providing on-site sanitation and opportunities for nutrient and resource recovery. This mini-review summarises the efforts to valorise human waste and process routes for the recovery of value-added products. These involve a review of ecological sanitation, systems that safely collect and treat human waste in-situ and advanced waste-to-energy systems to convert recovered materials to fuels, heat and/or electricity. Focus is given to low-cost technological solutions that offer ecological benefits and opportunities to recover useful products. The barriers and opportunities to the adoption of on-site sanitation and appropriate technologies are discussed, considering current limitations and potential benefits. There are opportunities to recover useful products from human wastes; however further research is needed to ascertain the value and impact of recovered products.

23. Introduction

The use of human excreta as fertiliser has been around for as long as we know (Shiming, 2002). Until the 1900s, it was socially acceptable in many Nordic countries to use human excreta from dry pit latrines for arable farming (Heinonen-Tanski et al. 2005). The use of night-soils (bio-solids collected from cesspools, pit latrines, septic tanks) on agricultural fields were commonly practised in countries like China, Vietnam, Japan and India (Phuc et al. 2006), but the increasing use of chemical fertiliser, invention of the modern flush toilet and growing environmental and health concerns have caused such practices to face near-extinction (Ferguson, 2014). The current urban sanitation systems are on the verge of facing a similar fate because the linear approach to managing waste raises environmental concerns, particularly in resource and nutrient recovery. For example, the conventional flush toilet requires at least 2 L of freshwater per flush (Hu et al.2016) to convey waste from individual units to a centralised treatment plant and via a broad network of sewer infrastructures that combine storm drain, commercial wastewater with domestic sewers. These processes require a considerable amount of energy, capital investment and land space, which is particularly challenging for developing countries. Often, communities do not benefit from centralised water and energy services and settlements are densely populated, clustered or distant apart (Montgomery et al. 2007). Even when infrastructures are present, systems are largely

Tosin O. Somorin
University of Strathclyde
tosin.somorin@strath.ac.uk

dysfunctional, due to improper use and maintenance of sewer networks. In many communities, proper waste treatment and disposal methods are rarely followed, and toilet facilities are often shared, limited or unimproved (WHO/UNICEF, 2017). There are reports of pit latrines and sewers leaking into groundwater sources (Odagiri et al. 2016), illicit dumping of sludges retrieved from septic tanks and pit latrines into the environment (Orner and Mihelcic, 2018) and practices of open defecation. The development of decentralised sanitary solutions is, therefore, a priority and opportunities to manage, recover and utilise human waste are being explored globally.

There are various propositions for the development of onsite sanitation systems, solutions that can safely collect and treat human waste in-situ and by-products of value. Technological solutions are expected to operate without depending on an external supply of water, energy and infrastructures. Multiple tangible benefits e.g. clean water, nutrients, fuels are demanded from the recycling of waste resources. The values of end-products are projected to exceed the cost needed to transform waste and systems must not compete with universal human needs e.g. nutrient recycling for food production or strain the natural environment. This mini-review summarises the effort to derive value from human waste. Valorisation of waste is examined in the context of nutrient recovery and for advanced fuels, heat and/or electricity. Focus is given to low-cost approaches and technological solutions that offer ecological benefits and opportunities to recover nutrients and/or value-added products. The barriers and opportunities for the adoption of on-site sanitation and appropriate technologies are discussed to inform future research programmes.

23.1. Human excreta as a resource

23.1.1. Human Urine

Urine contains large amounts of organic solutes and inorganic salts (Heinonen-Tanski et al. 2007). On the average, a healthy adult produces 0.6 – 2.6 L of urine per day (Rose et al. 2015), which contains about 300 – 2200 mg/L of potassium and 150 – 1800 mg/L of phosphorus (Simha et al. 2017). Urea is the most predominant form of organic nitrogen (N), making up 50% of the organic solids and 75 – 90% of nitrogenous fractions (Rose et al. 2015). The rest are mainly organic and inorganic salts e.g. phosphorus (P) in the form of superphosphate, potassium (K) as ionic salts and organic ammonium salts (Lind et al. 2001). The dry solids contain about 14 – 18 % N, 13% carbon (C), 3.7% P and 3.7% K (Rose et al. 2015), nutrients that are readily accessible to plant and microbes. The release of nutrients offers several advantages: it encourages the formation of microbiota and humus, improves water retention and adsorption in soils and expands soil structures (Singh et al. 2017). Low concentration of metals in contrast to synthetic fertiliser is also considered a benefit as it minimises toxicity (Simha et al. 2017), but crop yield depends on the proportion of nutrients. Typically, nutrients become available when organics such as urea breaks down into constituent parts: ammonium (NH_4^+), ammonia (NH_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). The proportion of NH_4^+ and NH_3 progressively changes due to increasing pH, leading to the release or loss of nutrients (Harder et al. 2019). According to Rose et al. (2015), body water balance e.g. perspiration, respiration and urination affect the partitioning of nutrients in urine. This is influenced by factors such as fluid intake, diet particularly protein, salt and water consumption, diseases, physical exercises, environmental factors etc. Low concentrations of essential macro and micro-nutrients in urine can hinder growth and increase susceptibility to diseases. The inappropriate use and/or disposal can cause algal bloom, eutrophication, fish death, human intoxication (Gilbert et al. 2006; Finlay et al. 2010; Johnson et al. 2010). There are reports on urea – N and P pollution in rivers, which are attributed to leaching of nutrients through soils into surface water and groundwater sources (Drewry et al. 2006; Sun et al. 2012). For these reasons, recent focus is increasingly directed at nutrient extraction rather than direct use of urine.

23.1.2.Human Faeces

Faeces are about 75 wt.% water and 25 wt.% dry solids (Somorin et al. 2016). An average healthy adult produces 150 – 250 g of faeces but this can vary widely from 15 – 1505 g/cap/day (Rose et al. 2015), depending on age, dietary intake, geographical location, economic status, ethnicity, gender, health conditions etc. About 50 wt.% of the water in faeces are said to be bound in bacterial cells and in complex biofilm matrix —mainly exopolysaccharides. Solids are primarily composed of undigested fat, protein and carbohydrate, but the proportion of bacterial biomass can be up to 50 wt.%, making up most of the protein (Rose et al. 2015). The composition of undigested fat varies from 2 – 8% (wet basis) with fatty acids and phosphoglycerides as by-products of bacterial and body metabolism. Undigested carbohydrates make up about 25% of the solids and are dietary products, unlike protein that is formed from several sources including dietary protein, nucleic acids, bacterial metabolism and intestinal cells. Figure 23.1 outlines the physical and chemical characteristics of human faeces and urine. These resources are useful for increasing soil fertility and crop yield (Jensen et al. 2008; Mnkeni et al. 2009; Semalulu et al. 2011; Andersson, 2015) but pose potential health risks due to high numbers of enteric pathogens. The threats to direct use of wastes can also include foul odour, flies' infestation, helminth risks, itchiness and foot rot (Cofie et al. 2006). There have been several cases of transmission of helminths eggs (Carlton et al. 2015) and concern on accumulation and amplification of pollutants in the food chain due to the presence of organic pollutants, pharmaceutical residues and steroid hormones (Escher et al. 2005). Like urine, the chemical composition can vary in individuals, leading to yield variations. As such recent efforts are exploring ways to safely sanitise faecal sludge in a way that it improves global sanitation goals, reduces environmental pollution and brings economic gains. Source separation of human waste, stabilization of faecal sludge by composting and co-digestion with organic materials, are being explored as opposed to direct use of wastes on farms (Winker et al. 2009).

Faeces Composition

Generation Rates
(*Rose et al. 2015*)
Children: 75-364 g person^{-1} d^{-1}
Adult: 35-796 g person^{-1} d^{-1}

(Rose et al. 2015; Simha et al.2017)

LHV: 19-22 MJ/kg db
pH 5.3-7.5
Electrical Conductivity: 3.3 mS/cm
COD: 32-43 mg person^{-1} d^{-1}
BOD: 46-96 mg person^{-1} d^{-1}

Macro-nutrients (Rose et al. 2015; Simha et al. 2017)

Tot-N: 0.9-4.9 g person^{-1} d^{-1}/ 41 ± 4 g/kg
Tot-P: 0.35-2.7 g perso^{-1} d^{-1}/ 1.83-9.86 g/kg
Tot-K: 0.2-2.52 g person^{-1} d^{-1}/ 1.78-7.16 g/kg
NH_4^+N: 0.1-0.2g person^{-1} d^{-1}
NO_3^-N: 829-1678 µg kg^{-1}

Micro-nutrients (*Rose et al. 2015*)

Sodium: 0.12-4.1 g person^{-1} d^{-1}/ 0.8-4.94 g/kg
Calcium: 0.1-3.6 g person^{-1} d^{-1}/ 2.68-4.27 g/kg
Magnesium: 0.15-0.34 g person^{-1} d^{-1}/ 0.93-2.86 g/kg
Chlorine: 0.09 g person^{-1} d^{-1}/ 0.6 g/kg
Sulphur: 0.12-0.2 g person^{-1} d^{-1}/ 0.87 g/kg
Copper: 1.02-2.1 mg person^{-1} d^{-1}/ 6.8 g/kg
Iron: 30-1000 mg person^{-1} d^{-1}/ 200 g/kg
Lead: 0.02-1.26 mg person^{-1} d^{-1}
Manganese: 24-90 mg person^{-1} d^{-1}
Molybdenum: 2-4 mg person^{-1} d^{-1}/ 0.12-6.38 g/kg
Zinc: 5-13.31 mg person^{-1} d^{-1}/ 43.86-67.49 g/kg
Nickel: 0.08-0.3 mg person^{-1} d^{-1}/ 1.15-1.52 g/kg
Chromium: 0.02-0.18 mg person^{-1} d^{-1}/ 0.31-0.91 g/kg
Cadmium: 0.07-1.26 mg person^{-1} d^{-1}/ 0.27-6.39 g/kg
Mercury: 0.007 mg person^{-1} d^{-1}/ 0.04 g/kg

Proximate Composition
(Onabanjo et al. 2016)

Volatile Matter: 51 ± 2 wt.% db
Fixed Carbon: 32 ± 21 wt.% db
Ash: 17 ± 1 wt.% db

Volatile Matter: 12 ± 6 wt.% arb
Fixed Carbon: 7 ± 5 wt.% arb
Ash: 4 ± 1 wt.% arb
Moisture Content: 77 ± 4 wt.% arb

Elemental Composition
(Onabanjo et al. 2016)

Carbon: 51 ± 2 wt.% db
Hydrogen: 7 ± 0 wt.% db
Oxygen: 21 ± 3 wt.% db
Nitrogen: 4 ± 1 wt.% db
Ash: 17 ± 1 wt.% db

Microbial Load

Bacteria ($1e^{10}$)/g
Viruses ($1e^{5}$)/g
Helminths ($1e^{4}$)/g
Protozoa ($1e^{5}$)/g

Other Constituents

Undigested fat
Protein
Polysaccharide
Microbial biomass
Gut secretions
Cell shedding
Ash

Urine Composition (*Rose et al. 2015)*

Generation Rates
Adult: 0.6-2.6 L person^{-1} d^{-1}

Chemical Composition
Water: 91-96 wt.% arb
Organics: 65-85 wt.% db
Urea:1.36-35 g person^{-1} d^{-1}
Creatine: 0-0.15 g person^{-1} d^{-1}
Ammonia: 0.34-1.3 g person^{-1} d^{-1}
Macro and micro-nutrients

Carbon: 6.87 g/L db / 3.7% TS
Hydrogen: 1.51 g/L db / 3.7% TS
Oxygen: 8.25 g/L db / 3.7% TS
Nitrogen: 8.12 g/L db / 14-18% TS
Tot-K: 300-2200 mg L^{-1} / 3.7% TS
Tot-P: 150-1800 mg L^{-1} / 0.4-0.71 g person^{-1} d^{-1}
Tot-N: 1.8-17.5 g L-1 / 4.2-11.0 g person^{-1} d^{-1}
PO_4-P: 205-2500 mg L^{-1}
NH_4^+-N: 120-8570 mg L^{-1}
NO_3^-N: 0.438 ± 0.071 g L^{-1}
NH_3^-N: 0.34 ± 3.37 g L^{-1}
NH_4^++ NH_3^-N : 415 ± 30 mM / 200-730 mg L^{-1}
$CO(NH_2)_2$: 2.7-21.4 g L-1 / 10-35 g person^{-1} d^{-1}
Ca: 0.057-0.50 g person^{-1} d^{-1}
Mg: 0.19-0.21 g person^{-1} d^{-1}
SO_2^{-4}1.34-1.63 g person^{-1} d^{-1}
Na: 0.082-4.53 g person^{-1} d^{-1}
pH 5.5-7.0
Electrical Conductivity: 13.4-270 mS cm-1
COD: 7660±4630 mg L^{-1} / 8.5 g person^{-1} d^{-1}
BOD: 46-96 mg person^{-1} d^{-1}

Microorganisms

Bacteria contamination e.g. *Salmonella typhi, Salmonella paratyphi, Leptospira interrogans*
Helminth e.g. Schistosoma haematobium

Fig. 23.1: Physical and chemical characteristics of human faeces and urine

23.2. Source Separation of Human Wastes

The concept of separating human excreta from other waste streams is common to all ecological sanitation systems. Toilets are designed to receive human waste as a mixed stream or split-collect the waste such that urine is collected separately from faecal matter and without the addition of rinse water (Semiyaga et al. 2015). Processes are said to follow a “sanitise and recycle” model where waste streams undergo a form of biological treatment to limit pathogens and recovered bio-solids can be used as nutrients. The approach is increasingly becoming important because of the growing awareness that nutrient recovery from wastewater is costly and unsustainable. According to (Spångberg et al. 2014), human urine contributes more than 80% of the total N and more than 50% of the total P and K in wastewater, although the volume fraction of the urine treated is <1%. While efforts are increasingly tailored to recover nutrients from wastewater, these often cannot be achieved and if at all, <10% because of biological decomposition, chemical pollution and mass dilution of waste streams. Section 23.2.1-4 describes some of the ecological sanitation systems (EcoSans) and the benefits and challenges for their use in source separation of human wastes.

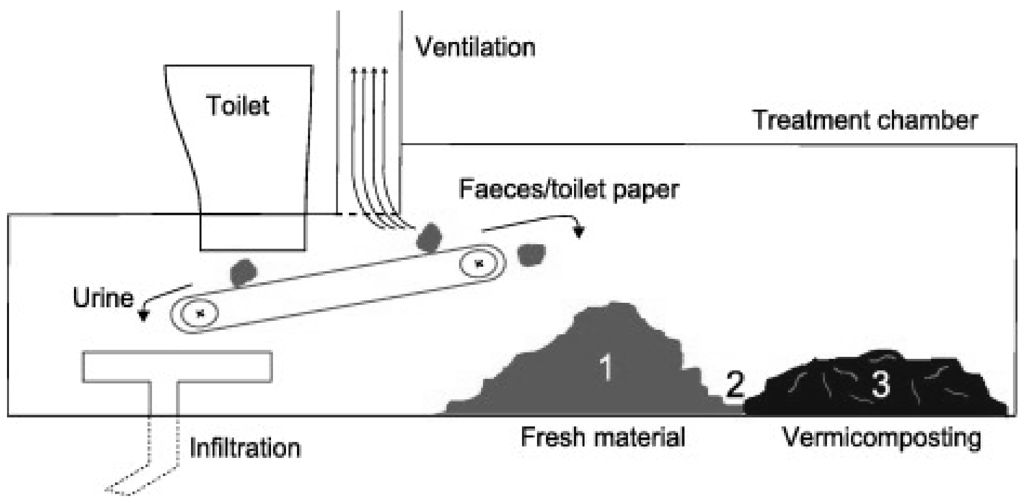
23.2.1. Composting Toilets

Composting toilets are referred to as dry toilets because they do not require water, and as biological systems rely on microorganisms to decompose faecal matter to a useable organic form, known as compost. There are several variations of composting toilets: compact or large, with single or multiple composting tanks, electric or manual toilets, waterless or water-based, with source separation of urine or mixed reception of human wastes (Anand and Apul, 2014). Typically, the system consists of: i) a user-interface ‘toilet bowl’ which can be plastic, ceramic, or fibreglass, ii) composting tank, iii) accessories such as connecting vent pipe and drain that removes odour and excess leachates. These components can be disconnected from water and wastewater infrastructures. Like conventional flush toilets, the faecal waste is deposited in the toilet but then transferred into the composting tank where it is digested under aerobic conditions. In the process, carbon dioxide (CO_2), water, and heat are generated. The heat generated raises the temperature of the matrix and improves moisture evaporation. It also maintains suitable growth conditions for thermophilic microorganisms. Factors such as moisture, temperature, aeration, pH and porosity affect the yield of products (Zavala et al. 2005). To encourage the growth and survival of microorganisms, a well-balanced aeration and moisture control system is required at relatively high temperatures of 50-60^{o}C (Singh et al. 2017).

Co-composting with organic materials such as wood/sawdust, agricultural wastes, food wastes or organic fractions of MSW is recommended. This is because faecal sludge is rich in nutrient but high in moisture content. However, organic materials such as wood dust and organic fractions of municipal solids wastes have a bulky matrix and when mixed with faecal sludge, porosity and water retention improves, which maintains carbon-to-nitrogen ratio at optimum levels. The system benefits from deactivation of pathogens and helminth eggs (usually within 3 weeks of operation) and the resulting compost is humus-rich and malodour free. The process is, however, a disadvantage because it is not instant: it requires about 10-12 weeks, depending on the scale and operating conditions. It requires external energy supply to keep temperatures and aeration stable, except for manual operation. It requires technical skills, which is often lacking in rural settings. Two main challenges with the use of human compost for agriculture: toxicity and pathogenicity. While human faeces have low toxicity, the biochemical processes that occur during compost can cause the accumulation of toxic compounds. Chemicals, such as antibiotics and hormones can reduce the effectiveness of microorganisms to degrade organics in time. Microorganisms also have an antagonistic relationship with other organisms, leading to inhibition, nutrient depletion and death of indigenous organisms and growth of unwanted species. While temperature is s a useful measure to determine the safety of compost, it does not accurately measure the entire compost or bioactivity unfolding in the compost (Anand et al. 2014), as such mixing to maintain uniform temperatures and combinatory tests are suggested for safe quality. In open systems, the volatilisation of ammonia cannot be avoided, which poses risks to the environment.

Some composting toilets employ earthworms by a process known as vermicomposting. Unlike conventional methods, vermicomposting does not require high temperatures and the end-products are earthworm biomass and vermi-rich compost, which are useful for farming and for soil conditioning (Hill et al. 2012; Lalander et al. 2013). The earthworms can decompose a wide range of organic materials, but moisture level needs to be maintained at 50-60% (Singh et al. 2017). The process is more rapid, easily controllable, energy-efficient, and cost-effective. It ensures complete removal of pathogens and helminth eggs (Bajsa et al. 2004; Yadav et al. 2010); however, technical skills are required for operation and maintenance. Further, there is increasing interest in the use of black soldier fly, *Hermeticia illucens L* for decomposing human waste (Banks et al. 2014). The larvae feed on the sludge and in the process converts it to compost. The residue is highly rich in animal protein, about 32-64% of the dry solids. The larvae can serve as feed for poultry or fish. The process reduces the load of pathogenic microorganisms and helminths eggs, although further treatment is still required for compost of safe quality. Figure 23.2b shows a vermicomposting toilet with source separation of urine and faeces, followed by conversion of sludge to compost.

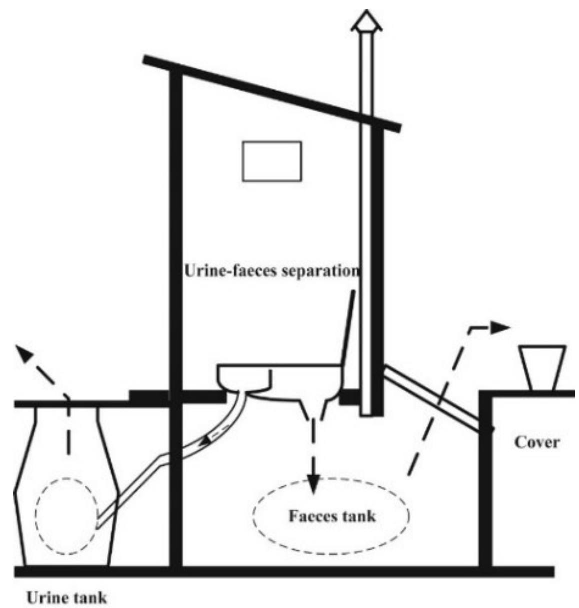
Fig. 23.2: Pictorial view of vermicomposting toilet (Lalander et al. 2013)



23.2.2. Urine Diverting Dehydration Toilets (UDDT)

These are also waterless toilets with a unique user-friendly interface that separate faeces and urine at the point of deposition (Lienert, and Larsen, 2009; Mkhize et al. 2017). The setup consists of: i) a squatting pan or toilet seat that is designed to separate faeces and urine at source, ii) vaults for dry faeces storage. These can be double dehydration units or single interchangeable containers, iii) a ventilation pipe to remove odour and moisture from the vault, iv) an anal cleaning area with a separate collection of wash water, v) a piping system and container for urine collection and, vi) a storage container with dry cover material. To prevent odour and flies, the faecal solids are collected in ventilated vaults or containers. Dehydration occurs via moisture evaporation and ventilation and because of the addition of dry cover material e.g. ash, lime, following every deposition. The system relies on dehydration and segregation, as such vaults and receivers need to be properly designed. There is reduced pathogen due to dehydration, but this is subject to holding time and other operational factors. The solids need further treatment to inactivate pathogens and helminths eggs. The vault can be connected to a composting unit or to a shallow pit for mineralization or periodically emptied for external treatments. Figure 23.3 shows a typical UDDT with source separation of waste and collection of the sludge material in a vault/tank.

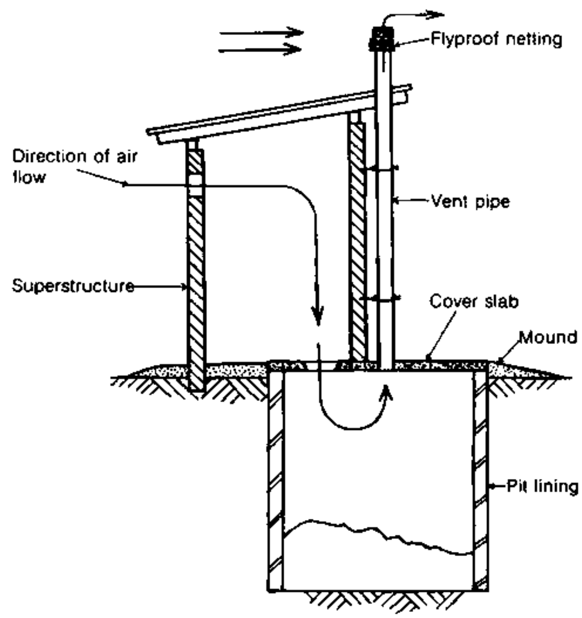
Fig. 23.3: Pictorial view of a Urine Diverting Dehydration Toilet (Hu et al.2016)



23.2.3. Ventilated Improved Pit (VIP) Latrine

These toilets consist of: i) an enclosed superstructure with gap for air circulation and facing the prevailing wind, ii) a pit for storage of human waste and connected to a ventilation pipe, iii) squatting pan, toilet seat or slab support structure that is centred over the covered pit and, iv) a ventilation pipe that forces the flow of air from the outside via the pit and through the pipe to the atmosphere. The continuous movement of air removes odour from the pit to the atmosphere. Integrated flyscreen in the pipe discourages flies and the hole allows free passage of air. The system relies on the movement of air as such the superstructure needs to be properly designed. Foul odours are expected when the ambient air temperature is colder than the air in the pit and prevents air circulation. The superstructure needs to be kept dark to ensure the effectiveness of the vent pipe in controlling flies, except mosquitos. They are proven methods for faecal sludge treatment and widely used in many countries. They are simple to use and easy to maintain, often requiring emptying every 12-24 months. Proper design of the VIP latrine can ensure sludge stabilisation, but it does not inactivate pathogens or helminth eggs. Post-treatment such as composting, vermicomposting, anaerobic digestion or drying are required. Figure 23.4 shows the pictorial view of a VIP latrine with a mixed collection of urine and faeces, and the direction of airflow that removes odour and prevent flies (Franceys et al. 1992).

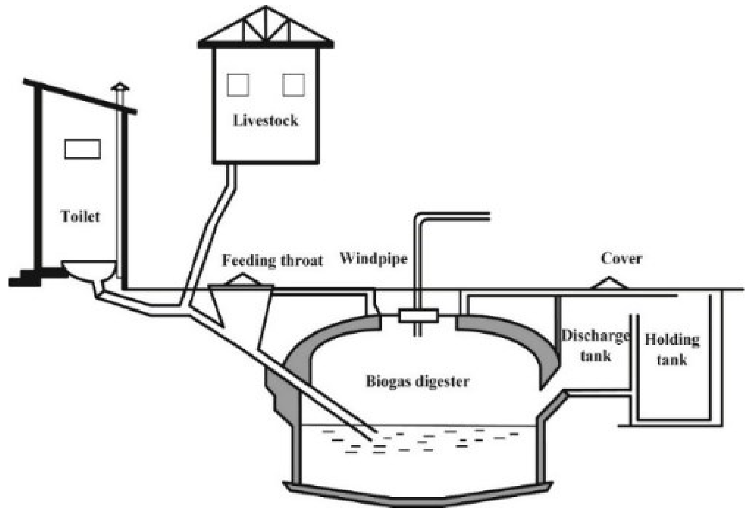
Fig. 23.4: Pictorial view of a Ventilated Improved Pit Latrine (Franceys et al. 1992)



23.2.4. Biogas Toilets

These toilets can be integrated with dry toilets e.g. urine-diverting dehydrated toilet. The process is well-suited for co-digestion with animal manure, food waste, sewage sludge and organic waste from municipal solid wastes. It relies on the actions of anaerobic microorganisms to decompose the organic materials to gas (mainly CH_4 and CO_2) and digestate, a process known as anaerobic digestion (AD). AD is a naturally occurring process for human faeces, from the human gut to septic tanks, although the end-products of natural processes are directly released into the environment. The process requires the absence of oxygen (O_2) and optimum temperatures of 25-40^oC for the growth of mesophilic organisms (wet digestion conditions) or 50-60^oC for selective growth of thermophilic organisms (dry digestion conditions). The digestate from the wet mesophilic process is high in water content: nearly a slurry if not dewatered. The digestate and those from the thermophilic processes are rich in N, P, K, magnesium (Mg) and sulphur, and valuable to produce fertiliser. The gas is methane-rich but needs to be upgraded due to moisture and unwanted gases such as CO_2, hydrogen sulphide (H_2S) that is present. The gas recovered is scrubbed with water and dried, then compressed to natural gas quality. The gas can then be used for cooking, lightning or electricity. While anaerobic digestion is largely suggested for treating human faeces, there is limited information on their application (Colón et al. 2015). Few studies (Snell, 1943; Park et al. (2001) that have examined the anaerobic digestion of undiluted human faeces show that up to 0.16-0.5 m^3 biogas can be obtained per kg of undiluted faeces but the yield can be inhibited when faeces are co-digested with wood/straw or urine. This is because straw is difficult to decompose, and urine increases alkalinity. Hence, source separation of faeces and urine, and co-digestion with organic materials such as food wastes are recommended. The use of advanced processes for concentrating the solids e.g. thickening has improved gas yield (Park et al. 2001). The process does not inactivate all the pathogenic microorganisms and helminth eggs, so digestate requires further treatment. It is expensive to build and can fail if poorly maintained, as such technical skills are required for operation and maintenance. The system requires land space and onsite sludge management for produced effluent. All these limits their application in rural and peri-urban areas. Figure 23.5 shows the pictorial view of a Biogas-based latrine with mixed collection of waste.

Fig. 23.5: Pictorial view of a Biogas Toilet (Hu et al. 2016)



All the above-mentioned EcoSan systems focus on deriving nutrients for agricultural or for enriching the soil. But, like conventional systems, EcoSans are prone to abuse and could lead to severe environmental pollution if improperly installed, used or emptied. They do need to be designed and operated appropriately to be considered hygienic. There are instances of technology abandonment of UDDT e.g. in Burkina Faso, due to system failure and progressive lack of interest to maintain and repair facilities. Some of the situations were caused by inappropriate designs, poor performance or considered to be against socio-cultural beliefs and norms (Phaswana-Mafuya et al. 2005). There were instances of refusal, hesitation and unwillingness to use the by-products for agriculture. There were cases of gas leakage, insufficient gas, and odours resulting from biogas latrines (Nakagiri et al. 2016), which stemmed out of lack of technical skills to operate and maintain these systems. Instances are cited on the frequent misuse of facilities, blockages with urine precipitates and faeces, overfilling of the vaults, improper segregation of urine and faeces, odour, flies, lack of spare parts for certain toilet models e.g. fans on chimney pipes. While most developed countries can benefit from the minimum regulatory requirement for toilet certification, communities that lack sanitation often must rely on user experiences to certify the use of a product. Thus, there is a need to tailor these sanitary solutions to user's needs and expectations, not only based on what is needed but aspired. This includes design considerations for system operation and maintenance, user interaction that promotes ease-of-use, understanding of how to operate and maintain the technology and, accessibility to repair and parts. Pre-feasibility assessment is not only required; long term project support is essential. A one-size fit model would not be appropriate, even when communities are clustered based on needs. Community listening programs and approaches that involve the user in the design of the technology has proven to be useful (Carter et al. 1999). Other factors such as political, legal and socio-cultural complexities play a role in adoption, thus the development and deployment of sanitation technologies are beyond solving a local need. Table 23.1 highlights the opportunities and barriers to adoption of EcoSan systems.

Table 23.1: Summary of Opportunities & Threats in Source Separation of Human Wastes

Advantages	Disadvantages
▪ Approach to faecal sludge management (FSM) promotes nutrient recovery, extraction and recycling. ▪ Appropriate use of methods improves sludge stabilisation and reduces pathogen risks. ▪ Provides basic sanitation and reduced options for open defecation. ▪ Provides financial incentives by providing alternatives to mineral fertiliser and resources, hence reduced requirement for chemical fertilisers. ▪ Low-cost installation compared to conventional sanitary systems ▪ Minimal energy requirements and applicable in low-income countries	▪ The technical complexity of biodigesters. ▪ Manual emptying poses risk to pit emptiers ▪ Continuous education needed to raise public awareness, ensure the correct use of facilities and to foster a change in attitude towards human wastes. ▪ Sludge and effluents often need further treatment ▪ The fate of pharmaceutical chemicals in treated wastes and their impact on the ecosystem is not clear ▪ Poor public acceptance of faecal sludge products and limited understanding of market potentials ▪ Associated costs of emptying pits on a regular basis e.g. every two years limit proper use of facilities ▪ Complementary nutrients might be required due to low concentrations of certain micro-nutrients.
Opportunities	**Threats**
▪ Nutrient use for fertiliser to increase crop yield and reduce the cost for agricultural farming ▪ Use of recovered nutrients in soils to improve soil moisture, water retention and soil structure. ▪ The reduced waste volume reduces storage capacities, transportation and processing requirements. ▪ Opportunities for local businesses e.g. faecal char and briquette production, fertiliser production etc. ▪ Use of biogas for power generation: reduces deforestation from the exploitation of wood biomass. ▪ Use of faecal char for fuels and biochar	▪ Uncertainty on long term effect of utilising waste. ▪ Bio-accumulation of micropollutants and bio-amplification in food chain ▪ Misuse of facilities leads to environmental pollution ▪ Transportation over long distances to recover sludge. ▪ Unwillingness to pay for infrastructure ▪ Increased sludge production but lacking infrastructures e.g. dewatering and energy system ▪ Capital costs for installing new sanitary systems

23.3. Solid-liquid Separation

Solid-liquid separation limits moisture in recovered solids and facilitates the removal of solids from effluent (Singh et al. 2017; Simha et al. 2017). To ensure safe and hygienic treatment of human waste and to improve the potentials of supplementing soils with nutrients and organic matter, processes involving sludge thickening, coagulation and flocculation and dewatering are often recommended (Mehta et al. 2015). This is because moisture levels in recovered faecal solids are still often as much as 70 wt.% and for systems that receive mixed waste streams, moisture can be up to 97 wt.%, although, source separation of waste streams limits the addition of water from other waste streams. For off-grid, low-income settings, the use of drying beds, geobags and Imhoff tanks (Singh et al. 2017), is often practised. Industrial processes involving belt filters, centrifugation, vacuum filtration, filter presses and sludge conditioning by heat can also be applied, but these have limited application in low-income countries, particularly in rural communities where they are most needed. In this respect, low-cost sludge thickening approaches involving the addition of lime, sawdust or fly ash and the use of drying beds are common practice. Studies by Cofie et al. (2006) showed that drying beds effectively dewatered and removed helminth eggs from faecal sludges, but results varied, depending on the quality of the filtering medium, degree of stabilisation of faecal sludges, loading rates, bed height and on external conditions (e.g. rainfall and ambient temperature). Seck et al. (2014) showed that drying rates improved in drying beds when faecal sludges were mixed during loading but covering the bed provided no significant additional benefits. Typically, drying beds are designed as receiving troughs with open bed of sand and gravel through which effluents percolate and moisture evaporates. They can be covered or uncovered, mixed or unmixed and planted or unplanted (Seck et al. 2014; Sonko et al. 2014). Long residence times, high land space requirement and the need to treat the resulting effluent limit their application. With geobags and Imhoff tanks, land requirements are minimal, but pathogens are only slightly reduced, and solid and liquid waste streams require further treatment. A number of research activities are on-going to effectively dewater and dry faecal sludges such that the by-products can be safely used as a fertiliser or further converted to fuel, heat and/or electricity. The removal of moisture reduces unpleasant odours, eliminate pathogens and improve longevity and quality of end-products. The reduction of waste volume limits storage, transportation and process requirements. The choice of treatment will depend on costs, space availability, location, quantity of wastes to be treated and requirements for the end-products etc. Preliminary screening and treatment processes might be required to prevent unwanted materials e.g. plastics, textiles. Thermal processes and solar dryers (Septien et al. 2018a) are being developed to provide these added benefits.

Table 23.2: Examples of Solid-liquid Processes for Faecal Sludge Treatment (Singh et al. 2017)

Sludge Dewatering	**Design Criteria**	**Removal Efficiency**	**Description**	**Advantages**	**Disadvantages**
Unplanted Drying Bed	100-200 kg TS/m^2/year	>95% SS 70-90% COD 100% HE	A shallow filter filled with sand and gravel with an under-drain to collect leachate	Low-cost. Good dewatering efficiency. No energy requirement. It can-be constructed locally. Suitable for peri-urban and rural communities.	High land requirement. Long residence times. Promote odours and flies. Labour-intensive. Limited reduction of pathogens. Further treatment required for both solid and effluent waste streams. 0.05 m^2/capita/10-day for unplanted drying beds and 4000m^2/MLD
Planted Drying Bed	<250 kg TS/m^2/year	96-99% SS 95-98% COD 70-80% TS	Constructed wetland with aquatic plants, bacteria, fungi and algae that can decompose and extract nutrients from waste.	Cost-effective. Easy to operate and can handle high loading rates. Improved sludge treatment to unplanted beds.	
Centrifugation	Depending on the amount of waste treated.	85-99% SRE	Mechanical dewatering relies on centrifugal force of rotation, and the difference in density between the solid and liquid waste. Solids accumulate and liquids can be decanted.	Compact with minimal land space requirement. High solids recovery efficiency and suitable for different sludge types and composition. Suited for urban areas.	External energy required. Technical skills required. High power consumption. High operational and maintenance costs. High noise levels. Specialist knowledge for maintenance.
Settling-Thickening Tank	SAR: 0.13 m^3/m^3 of raw faeces. Residence time:>4 hours	57% SS 24% COD 12% BOD 44% HE	An effluent holding tank where FS enters at one-end and supernatant exits at the other end. Settleable solids concentrate at the bottom of the tank. Scum floats on the surface. Lime/Ammonia may be added to reduce pathogens, odours and to precipitate chemical compounds.	Relatively robust. 0.006 m^2/capita land required Continuous processes requiring minimal operating and maintenance requirements. Suitable for peri-urban and rural communities	It requires lime/ammonia addition to improve efficiency and to reduce odour. Pathogens concentrations are only slightly reduced. Further treatment required for both solid and effluent waste streams
Imhoff Tank	-	50-70% SS 30-50% BOD	A two-story tank mechanism that utilises the force of gravity for the separation of solids. The process is based on sedimentation	Relatively low land requirement (600m^2/MLD). Low-cost operation and maintenance. Ideal for urban areas including densely populated regions.	Requires land space and structure with depth; hence not suitable for high water table areas; low reductions of pathogens; effluent and scum require further treatment
Geobags	-	-	Permeable textiles made into geotube containers Geo-bags used for dewatering the wet sludge	Economical viable, no excessive and constant labour, no frequent maintenance required. Suitable for peri-urban and rural communities	Drying required prior to composting to reduce pathogens and helminths

TS, Total solids; SS, suspended solids; BOD, biological oxygen demand; COD, chemical oxygen demand; HE, helminth egg; SAR, solid accumulation rate; SRE, solid recovery efficiency; MLD, mega litres per day, FS, faecal solids

23.4. Processing of Liquid Waste Streams for Nutrient Recovery

The effluent from sludge dewatering processes (e.g. percolate from drying beds) and urine from source-separated waste streams can be processed to extract nutrients. Methods such as membrane filtration and precipitation are often mentioned in literature for selective removal of enteric pathogens and nutrients (Ronteltap et al. 2007; Heinonen-Tanski et al. 2007; Etter et al. 2011). Methods such as ozonation (Bougrier et al. 2006), adsorption/ion-exchange (Inglezakis and Poulopoulos, 2006), ammonia stripping (Lei et al. 2007), reverse osmosis and forward osmosis (Hasar et al. 2009), have been employed for effluent treatment but limited work has been done in source-separated human waste. Membrane filtration concentrates effluents across a semi-permeable membrane and depending on size and configuration, selected nutrients can be recovered from the permeate. The method offers opportunities to accumulate, release and extract nutrients. The drawback of membrane filtration is that it is prone to fouling which also reduces lifespan and increases energy use. The retentate accumulates useful nutrients and pollutants, which can promote nutrient loss (Monfet et al. 2018; Mehta et al. 2015). Precipitation is well applied for wastewater treatment and relies on the addition of a chemical compound (coagulant) to separate nutrients from waste streams (Harder et al. 2019). The most applied method of precipitation in urine involves the addition of Mg salts to urine waste streams in order to remove nutrients such as P (Ronteltap et al. 2007). The mixture yields precipitate, which could be Mg ammonium phosphate (MAP), Mg potassium phosphate (MPP) in the absence of ammonium. Other ionic salts can also be targeted including calcium phosphate, aluminium phosphate, sodium phosphate or aluminium phosphate (Harder et al. 2019). Ultimately, precipitate can be used as fertiliser, which reduces the environmental concerns on pharmaceutical products and residues in urine. The slow tendency to release nutrients is considered an advantage for farming in areas close to water sources and for certain crop types, e.g. sugar beets (Rahman et al. 2014). The struvite is colourless and odourless, as such effort to use it for fertiliser production is expected to improve low social acceptance for direct use of human urine. Other advantages include low capital requirements, ease of application and the purity of precipitate. The drawback of this approach involves the associated costs for the use of salts, recovery of nutrients and production of fertiliser, values that are similar for synthetic fertilisers. Also, the nutrient recovery process focuses on superphosphate and ammonium N, as such other organic nutrients can be disregarded, leading to nutrient loss.

23.5. Solids Processing for Energy and Value-added Products

23.5.1. Thermal Processes

Human faeces can be subjected to heat, with or without the presence of oxygen, to produce energy carriers such as biochar and biogas (Afolabi et al. 2015; Andriani et al. 2015) and/or to generate heat and/or electricity (Onabanjo et al. 2016a; Hanak et al. 2016). A brief description of appropriate technologies for processing recovered solids from human waste is provided in section 23.5.1-23.5.5 with details on potential routes for recovery of value-added products and conditions for conversion of wastes via thermal and biological processes. Some of the methods have been applied in principle, others are proposed and being developed; hence advantages and disadvantages are discussed in the context of potential application in faecal waste treatment.

23.5.2. Pyrolysis

Pyrolysis is traditionally used in the production of charcoal and has been in existence before the widespread of coal (Basu, 2010), as such, an old and proven technology. It requires oxygen-depleted environment and moderate temperatures of 300-650°C to thermally degrade carbon-based materials to char, oil and gaseous end-products. The process is increasingly becoming important because oil yield of up to 75 wt.% can be obtained (Bridgewater,1999). Moderate temperatures, rapid heating rate of up to 1000°C/min and short vapour residence time of <2s are conditions that favour the yield of the bio-oil. The rapid heating breaks down organic compounds while short residence time ensures that the recovered vapour does not further decompose, and secondary reactions and intermediate products are avoided. To favour the production of gas, high temperatures and long residence time are necessary; however gaseous products are atypical. For char yield, low temperatures and long vapour residence time are recommended, a process that is defined as slow pyrolysis and of great interest in faecal sludge management (Ronsse et al. 2013; Fakkaew et al. 2015a). Faecal char can be used in traditional furnaces and kiln, and as a substitute fuel for domestic heating and cooking. Since char is mainly composed of carbon with less oxygen and hydrogen, it is a useful form of carbon sequestration. This can improve aeration and soil quality and enhance water and nutrient retention for plant growth. The material is also considered useful for soil reclamation and remediation because of their absorptive properties. All these benefits will need to be proven, as there are debates on the use of faecal char for agriculture. The nutrient in char is said to be depreciated when compared to compost because the organic matter is lost during heating. There are studies that have showed that bio-char from other biomass can suppress crop yield (Van Zwieten et al. 2010; Sohi et al 2010), as such further research is required to confirm the benefits from faecal char. The yield and proportions of end-products depend on a number of factors including temperature, heating rate, pressure, residence time and feedstock parameters such as size, composition, moisture content and type. To demonstrate the use of pyrolysis for waste conversion and the effect of operating conditions, Ward et al. (2014), Liu et al. (2018) and Gold et al. (2018) investigated the pyrolysis of faecal sludge for char production. Temperatures between 300°C and 750°C and heating rates up to 30°C /min were considered. The faecal char had HHV of 25.6 MJ/kg at 300°C, a value that is comparable to the HHV of sub-bituminous coal but decreased with increasing pyrolysis temperature. The char was further converted to faecal briquette by grinding and combining the char with materials such as molasses and lime. On commercial-scale (Figure 23.6), three pyrolysis plants in Warangal, Wal and Narasapur, India treat 15 000 L of septic tank per day and generate biochar and pasteurised liquid (NIUA, 2015).

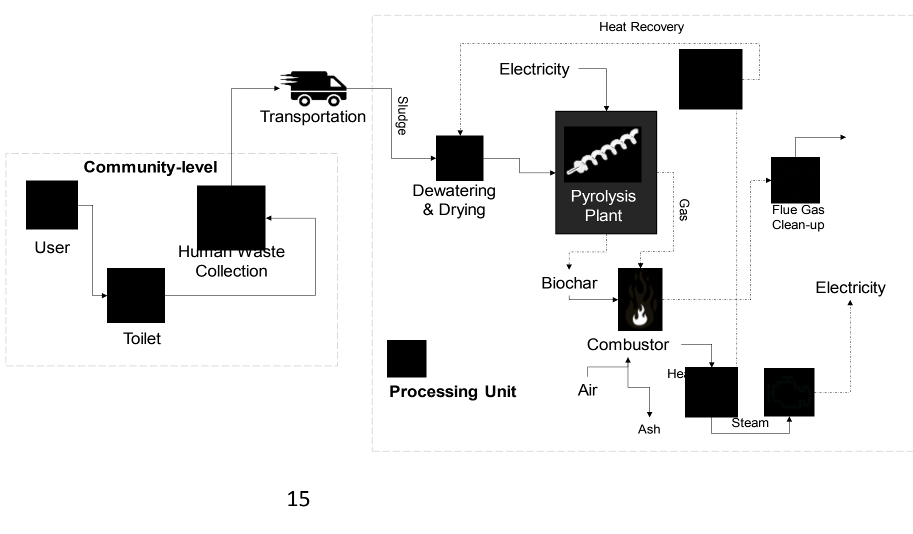
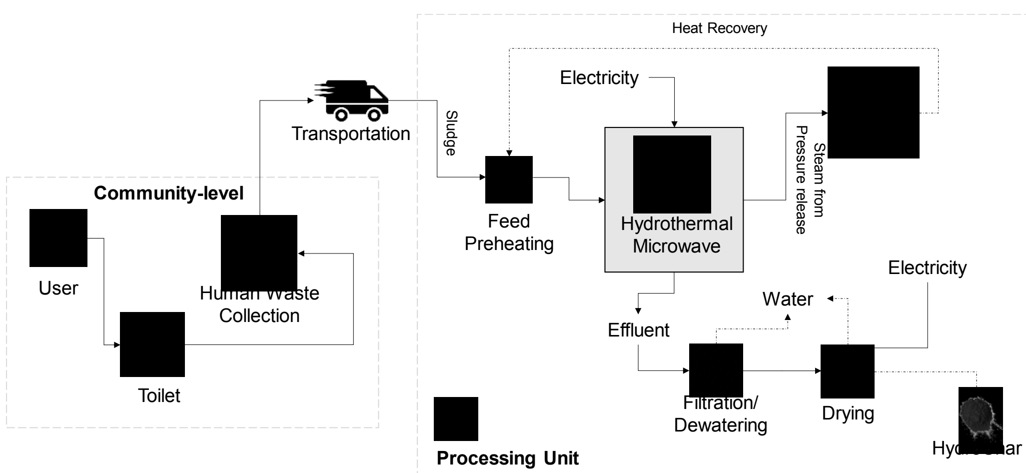


Fig. 23.6: Process Flow for Faecal Sludge Management via Pyrolysis

23.5.3. Hydrothermal Carbonisation (HTC)

Hydrothermal carbonisation, which is another form of pyrolysis, can process wet organic materials under relatively mild temperatures of 180-250°C and sub-critical pressure — conditions that enhance hydrochar formation and deactivate pathogens. It is one of the methods that are suited for human waste because it can handle highly moist feedstocks (<50 wt.%) with little or no pre-treatment requirement as opposed to conventional methods that rely on partially-dried or dried materials. The end-products are hydrochar, aqueous liquid and gas. The aqueous liquid is a mixture of dissolved organic and inorganic compounds with nutrients that are valuable for soil conditioning but cannot be directly released into the environment without prior treatment. The hydrochar is enriched with carbonaceous compounds, highly porous and valuable for soil conditioning (Fakkaew et al. 2015a). The drawback of this technology is that it requires high residence time (up to 12 hours) and relies on temperature gradients from convection and conduction for heat transfer and high pressures (up to 30 Bar). The heating regime is non-selective, as such uncontrolled temperatures lead to uneven heating. The energy yield of the hydrochar is relatively low for a highly energy-intensive process. The aqueous product that is formed as part of the carbonisation cannot be released into the environment without treatment and these reduce process efficiency and environmental gains. To reduce heating time, Afolabi et al. (2015) proposed the use of microwave-assisted HTC, considering temperatures below 200°C and residence time of 0.5 - 2 hours, as it offers a more precise heating profile for sludge treatment. The conditions reduce residence time of the fuel and improve uniform heating. Fakkaew et al. (2015b) proposed a two-staged HTC, where the direct conversion of the biomass that is governed by devolatilisation, intracellular condensation, dehydration and decarboxylation, is separated from downstream aqueous conversion processes such as hydrolysis, dehydration, decarboxylation, fragmentation, polymerization and aromatization. Studies by Koottatep et al. (2016) are on-going to apply additives and catalysts to accelerate thermal chemical reactions and to improve yield. Other studies by Danso-Boateng et al. (2013) and Fakkaew et al. (2018) show that the technology shows great promise but, all the technical concepts are at laboratory scales: none is yet to be commercialised. Figure 23.7 shows the process flow of managing faecal sludge using hydrothermal carbonisation.

Fig. 23.7: Process Flow for Faecal Sludge Management via Hydrothermal Carbonisation



23.5.4. Gasification

Gasification operates at relatively high temperatures of more than to 1000°C. Unlike pyrolysis that requires no oxidising agent, gasification requires a limited amount of oxidant (e.g. air, steam, nitrogen, CO_2, oxygen or a combination of these), to convert carbon-based material to char and gaseous end-products. Tar is produced as a black, viscous liquid but not desirable. The char that results from the process can be further valorised to improve tar cracking and convert unreacted carbon. This process has been studied using thermodynamic equilibrium model (Onabanjo et al. 2015), and in a 10-kW gasifier to investigate the maximum amount of sludge permitted from reliable operation and their performance with other feedstocks. While the process is feasible thermodynamically, there were problems with 100% use of faecal sludge in some of the gasification experiments: issues relating to agglomeration and clinkering. Operational faults and technical failures were attributed as the main cause of the problem, not necessarily the use of faecal sludge. The use of raw faecal sludge was not a feasible option; hence prior treatment and pelletisation were recommended to improve the heating value of the fuel. Other recommendations involve a) source separation of faecal solids to reduce high ash content, especially in toilets where ash and lime addition are encouraged. b) careful design of the feeding system to prevent crushing faecal pellets. c) use of additives to minimise clinker formation. d) co-pelletising faecal solids with other waste streams. Liu et al. (2014) proposed an advanced gasification process that combines plasma gasification and microwave technology to convert human faeces to syngas, which is then converted to electricity via solid oxide fuel cells. To make the system energy sufficient, part of the electricity produced from the fuel cell was used to power the plasma gasifier while the heat recovered from the syngas and exhaust gas was used for drying the waste. The technology is still under development; hence not on a commercial scale. Figure 23.8 shows the process flow at community scales using plasma gasification. For domestic sanitary applications, Jurado et al. (2018) designed and commissioned a flexible updraft and downdraft gasifier for continuous conversion of human faeces. The system depended mainly on gasification for converting the fuel to ash. In the downdraft configuration, the faecal biomass enters from the fuel hopper via the rotary valve while the gasifying medium (air) enters the reactor slightly above the grate. In the updraft configuration, the faecal biomass and ash have a similar pathway; however, the primary air enters from below the grate while the product gas exits from the top of the unit. The reactor also maintained other flexible options such as gas re-circulation path, air bypass mode and variable air heater settings. It was however limited to a few hours of operation due to the challenges of fuel bridging/channelling in the fuel hopper, poor movement and exit of the flue gas, and ash, as well as complex operation, as such, improved design was proposed. Further development has been completed; however, the is yet to be in commercial operation.

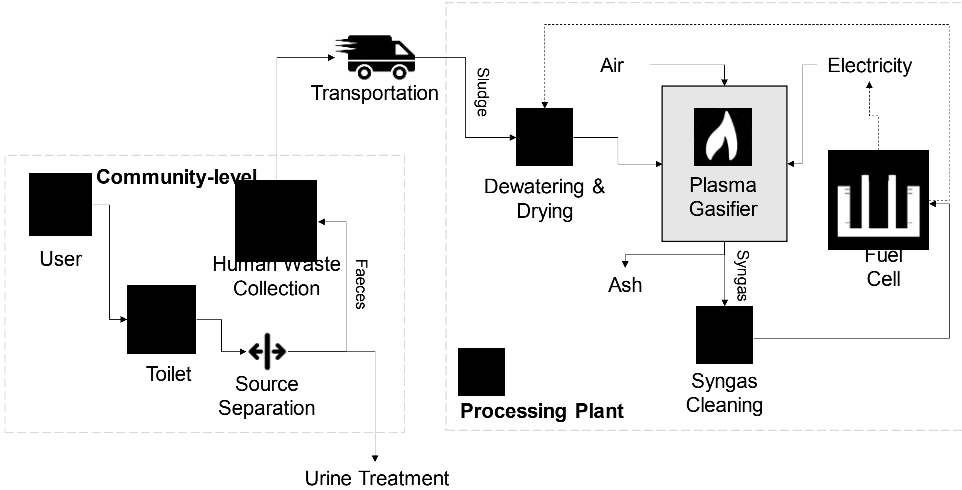


Fig. 23.8: Process Flow for Faecal Sludge Management via Plasma Gasification

23.5.5. Combustion

Combustion is a proven technology that holds great promise for faecal biomass valorisation. The process embodies heat and excess oxygen to thermal degrade materials and can be slow or rapid. The slow combustion, also known as smouldering, occurs at moderate temperatures of 250-700^{o}C without visible flame, but with progressive heat release. The fast process follows high temperatures (in excess of 1000^{o}C) with flame propagating outwards. Unlike pyrolysis that is largely an endothermic process and dominated by Boudouard reaction, combustion processes are exothermic and occur in the presence of sufficient oxidant and heat. The excess oxidant ensures complete conversion of the carbon-based material to CO_2 and H_2O, although other gaseous products such as CO, NOx and SOx are formed. Studies by Yerman et al. (2015) have shown that moist faeces can be treated at low temperatures and at various operating conditions using smouldering technology and synthetic and dog faeces. Operational parameters such as sand pack height and sand-to-faeces mass ratio need to be optimised. Flaming combustion has been demonstrated at laboratory scales by Onabanjo et al. (2016). Their studies show that human faeces with moisture content below 60 wt.% can be treated, provided operating temperatures are above 600^{o}C. The direct use of the material will require prior treatment and the minimum acceptable blend for treating moist faeces can improve by blending with wood dust. Figure 23.9 shows the process flow of managing faecal sludge at the household level using combustion. On large-scale (Figure 23.10), a large combustion-based facility known as “Omniprocessor” was installed in Dakar, Senegal to process faecal sludge and produce water and electricity. The unit produces about 10 ML of water per day with net electricity of 100 kW. A larger model is being developed to handle waste for 100,000 people with net electricity of 250 kW. The plant dries the faecal sludge, and the heat generated is used for producing electrical energy, part of which is used for drying and purifying water.

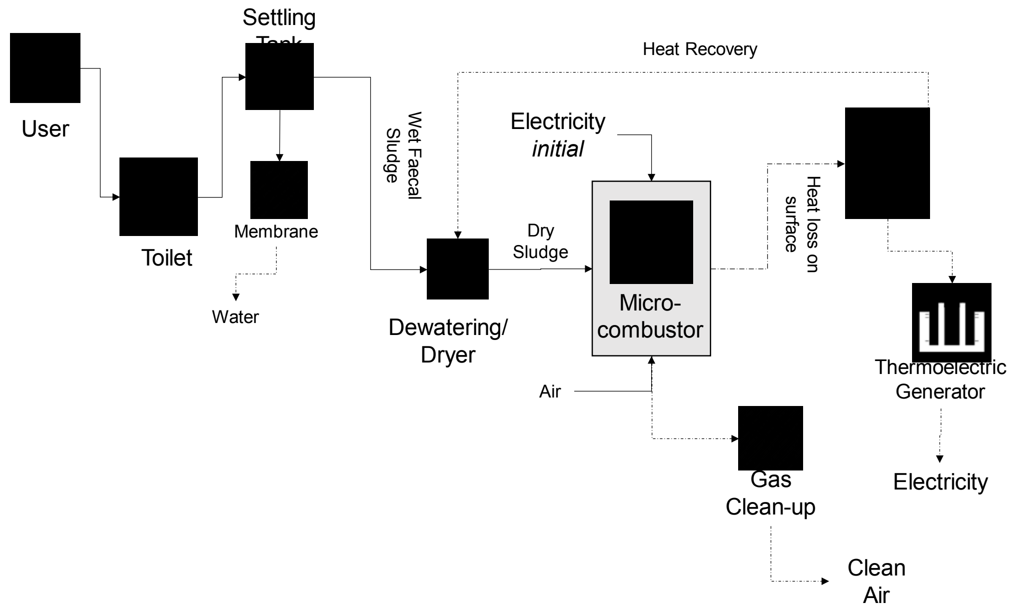


Fig. 23.9: Process Flow for Faeces Combustion at Household Scale

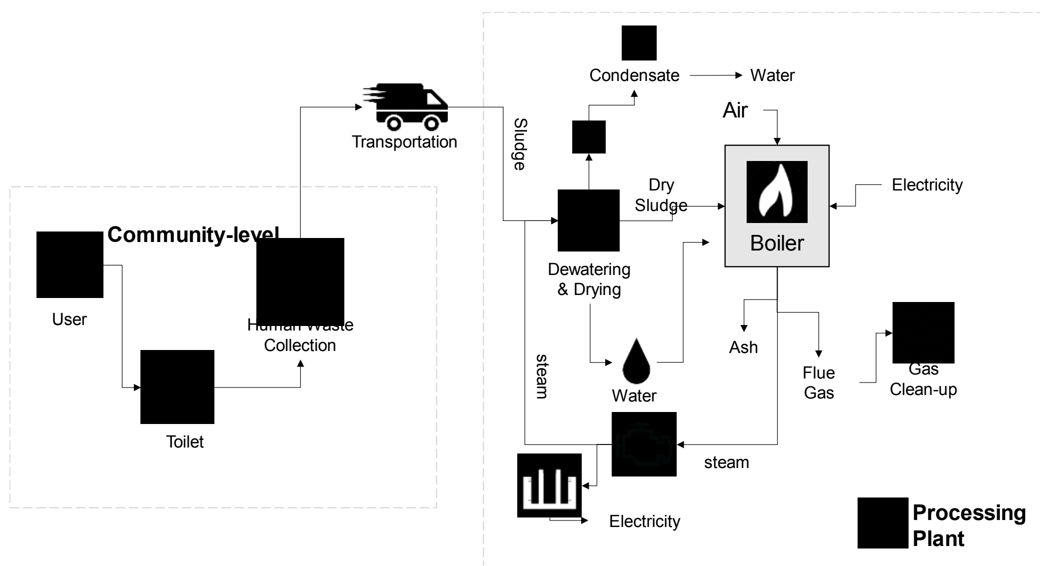


Fig. 23.10: Process Flow for Large Scale Combustion Facility

23.5.6. Biological Processes

There are several biological processes that can be applied for faecal sludge treatment. These processes can be integrated with on-site sanitation facilities as discussed in section 23.2.2 or developed as a stand-alone unit. Typically, processes rely on the ability of biological organisms to break down complex organic materials. For instance, anaerobic digestion depends on methanogens and the absence of oxygen to break down organic matter (Doble and Kumar, 2005). Biogas (mainly carbon dioxide and methane) can be recovered for subsequent conversion to heat and/or electricity and soluble nutrients for agricultural farming (Diener et al. 2014; Semiyaga et al. 2015). Other biological processes integrate composting (Zavala et al. 2005; Cofie et al. 2009), vermicomposting (Yadav et al. 2010) to decompose organic materials. The decomposition allows the recovery of soluble nutrients from the digestate, provided this done in a controlled environment as found in a digester/biogas plant. In an open system, volatile nitrogen forms are lost to the atmosphere and nutrients can also be lost in leachate (Harder et al. 2019), if not recovered. The added benefits of biological processes include the reduction of odours, inactivation of certain pathogens at temperatures above 60^{o}C, decomposition of organic pollutants, and further conversion of organic materials. This is particularly important for processes designed for nutrient recovery and for concentrated solid fractions. Factors such as retention time, feedstock composition, process temperature, feeding rate affect the yield and quality of end-products. The main disadvantages for biological processes are incomplete removal of heavy metals, micro-pollutants and other recalcitrant; hence these can accumulate in the digestate and limit their use. The process routes for the valorisation of source-separated solids are summarised in Table 23.3.

Table 23.3: Process route for valorisation of source-separated human wastes (faeces and urine)

Valorisation Route	Description	Design Criteria	Product Recovery (Efficiency)	Advantages	Disadvantages
Liquid Processing					
Membrane Filtration Ultrafiltration (UF) Microfiltration (MF) Nanofiltration (NF) Reverse Osmosis (RO) Forward Osmosis (FO)	Concentrate effluents across a semi-permeable membrane. Can remove suspended solids microorganisms and organic molecules and ions.	UF: 0.001–0.1 µm MF: 0.1–10 µm RO: 0.0001 µm	Permeate Rich in nutrients. UF (90-99%) MF (85-95%) NF (75-90%) RO (60-90%)	A simple physical process which does not require the addition of chemicals Relatively low operating and maintenance costs compared to other recovery routes. Nutrients can be used as fertiliser	Prone to fouling: reduced lifespan, efficiency and increased energy use. Pollutants accumulation and partial nutrient loss in retentate.
Chemical Precipitation e.g. struvite	Addition of salts e.g. magnesium, calcium aluminium, sodium etc.	-	Recovery of phosphate e.g. Mg Ammonium Phosphate, Mg Potassium Phosphate	The precipitate can be used as fertiliser	Cost of salts can be expensive Partial nutrient loss in the effluent
Ammonia Stripping via Air/Steam *Ozonation* *Photocatalytic Oxidation* *Electrochemical Oxidation*	Removes ammonia from liquid waste streams. Can be applied directly to digesters to reduce ammonia accumulation. Ammonia is oxidised into nitrate or nitrogen.	-	Ammonia	Stripped ammonia can be transformed into ammonium salts for chemical industries or fertiliser use	pH adjustment required Relatively high energy consumption for the value of the ammonia recovered.
Solids Processing					
Pyrolysis	Thermal degradation of carbon-based materials in the absence of oxygen and at moderate temperatures	Inert conditions. Temperatures: 300-850°C Pressure: 1 Bar	Bio-oil Char Heat Syngas (VOCs, CH_4, CO, N_2, H_2)	Less oxygen □fewer emissions. Useful products □gases, oils and char. Bio-oil can be used as feedstock for chemicals. Char can be used as soil conditioner. Syngas can be upgraded to chemicals (e.g. alcohols, alkanes) or used for fuels and energy	Endothermic process, the energy required Undermines nutrient recycling and recovery. Oil need for further upgrading to be used in internal combustion energy; hence energy consumption can exceed the value of recovery. Product recovery and net energy efficiency depend on system configuration and feedstock composition. Pre-treatment (e.g. drying) required for moist fuel.
Hydrothermal Carbonisation	Processes organic materials under relatively mild temperatures and sub-critical pressure.	Temperatures of 180-250°C. Pressure (up to 30 Bar)	Hydrochar, Aqueous liquid, Gas	It can handle highly moist feedstocks (<50 wt.%) with little or no pre-treatment requirement. The aqueous liquid is a mixture of dissolved organic and inorganic compounds with nutrients that are valuable for soil conditioning. Hydrochar is enriched with carbonaceous compounds, highly porous and valuable for soil conditioning.	High residence time (up to 12 hours) Uncontrolled temperatures lead to uneven heating. The energy yield of the hydrochar is relatively low for a highly energy-intensive process. The aqueous product cannot be released into the environment without treatment.
Combustion	Process embodies heat and excess oxygen to thermal degrade materials. Oxidising environment, excess oxidant (above stoichiometric). Smouldering at temperatures of 250-700°C. Flame combustion in excess of 1000°C).	Temperatures: 500-1200°C, depending on the application Pressure: 1 Bar Solid fuels with a high higher heating value above 14 MJ/kg	Heat Gas (N_2, O_2, CO_2 H_2O) Ash	Technology is more mature than alternatives. Commercially deployed at small and large scales. Can process fuel with low heating value.	Heat is the main end-product and product recovery depends on conversion efficiency and application. Ash disposal might be required if products contain pollutants. Gas requires further processing to avoid pollutant emissions. Pre-treatment (e.g. drying) required for moist fuel.
Gasification	Reducing, partial oxidising environment □sub-stoichiometric.	Temperatures: 500-1500°C, depending on the application Pressure: 1-45 Bar	Heat Gas (VOCs, CH_4, CO, N_2, H_2) Ash	Syngas can have heating value as much as 23 MJ/Nm3, depending on fuel composition Potential to produce hydrogen from renewable sources	Ash disposal might be required if products contain pollutants. Ash contains a relatively low level of carbon; thus, energy loss. Pre-treatment (e.g. drying) required for moist fuel.
Anaerobic Digestion	Methanogens break down organic matter in the absence of oxygen.	Relatively high temperatures of 50-60°C	CH_4, CO, Digestate	Biogas (mainly carbon dioxide and methane) can be recovered for subsequent conversion to heat and/or electricity and soluble nutrients for agricultural farming	Technical skills required. Capital costs for installation and maintenance of bio-digestors. Sensitive to feedstock. Digestate requires further processing.
Composting	Microorganisms (thermophilic and mesophilic) break down organic matter in the presence of oxygen.	Factors such as moisture, temperature, aeration, pH and porosity. Relatively high temperatures of 50-60°C	Heat CO, H_2O Compost	Deactivation of pathogens and helminth eggs. It requires about 10-12 weeks, depending on the scale and operating conditions. Aeration requires external energy supply to keep temperatures and process stable. The low investment cost for open systems. Effective fertiliser Can be applied at small-scale.	Chemical pollutants can accumulate in compost; thus toxicity. Microorganisms also have an antagonistic relationship with other organisms, leading to inhibition, nutrient depletion and death of indigenous organisms and growth of unwanted species. Chemicals, such as antibiotics and hormones can reduce the effectiveness of microorganisms to degrade organics in time. In open systems, the volatilisation of ammonia cannot be avoided, which poses risks to the environment.
Vermicomposting/Fly Larvae Composting	The process employs biological organisms e.g. earthworms or flies to break down organic matter	Moisture level needs to be maintained at 50-60%. Moderately low temperatures of 35°C	Heat CO, H_2O Compost	Compost rich in nutrients for farming and soil conditioning. The process is more rapid, easily controllable, energy-efficient, and cost-effective. The residue is highly rich in animal protein, about 32-64% of the dry solids.	Technical skills are required for operation and maintenance. A load of pathogenic microorganisms and helminths eggs are present and further treatment is required for compost of safe quality.

23.6. Conclusion

Human excreta (urine and faeces) can be recovered and converted to value-added products e.g. struvite for fertiliser production and faecal char for heat applications. However, in many parts of the world, these rich organic nutrient sources are disposed of inappropriately in the environment, where they pose risk to aquatic life, human health and the environment. This mini-review summarises the effort to derive value from human waste. Focus is given to low-cost technological solutions that offer ecological benefits and opportunities to recover nutrients and/or value-added products. Source separation of human wastes using EcoSan systems provide opportunities to recover and recycle nutrients, thus reduced pathogen risks and the requirement for chemical fertilisers, but if improperly installed and inappropriately used can lead to environmental pollution. Large amounts of sludge often result from these systems which require further treatment before it can be applied in practice. Biological processes can reduce odours and inactivate some pathogens, but micro-pollutants and other recalcitrant e.g. pharmaceutical residues can accumulate in the digestate, limiting their use. The controlled environment is needed to avoid the loss of nutrients but value-added products such as biogas can be recovered for heat and/or electricity. Thermal methods e.g. pyrolysis, gasification, hydrothermal liquefaction can also be applied, but nutrient recovery is limited; hence focus could be given to energy, fuels and/or chemicals. Irrespective of technological solution and product recovered, processes must not put strain on already limited resources and values of end-products must exceed the cost needed to transform waste. This can only be achieved if all benefits (e.g. avoided environmental health impacts, land-use savings, cost savings, water-use savings, nutrient recycling etc) are accounted. Poor public acceptance and limited understanding of market potentials can limit the use of faecal sludge products. Continuous education is necessary to raise public awareness, ensure correct use of sanitary facilities and to foster a change in attitude towards human wastes. Appropriate low-cost dewatering and energy conversion systems are needed at domestic and community levels for sludge treatment and to increase the adoption of EcoSan systems. Other resource routes can be explored such as the use of faecal solids as construction materials e.g. bio-brick formation. Further research is required to understand the long-time effect of utilising faecal waste streams, the fate of pharmaceutical products and bio-accumulation and bio-amplification of micro-pollutants along the food chain.

References

Afolabi OO, Sohail M, Thomas CP (2015) Microwave hydrothermal carbonization of human biowastes. Waste and Biomass Valorization 6(2): 147-157
Anand CK, Apul DS (2014) Composting toilets as a sustainable alternative to urban sanitation–A review. Waste management 34(2): 329-343
Andersson E (2015) Turning waste into value: using human urine to enrich soils for sustainable food production in Uganda. Journal of Cleaner Production 96: 290-298
Andriani D, Wresta A, Saepudin A et al (2015) A review of recycling of human excreta to energy through biogas generation: Indonesia case. Energy Procedia 68: 219-225
Bajsa O, Nair J, Mathew K et al (2004) Vermiculture as a tool for domestic wastewater management. Water Science and Technology, 48(11-12): 125-132
Banks IJ, Gibson WT, Cameron MM (2014) Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. Tropical Medicine & International health 19(1): 14-22
Basu P (2010) Biomass gasification and pyrolysis: practical design and theory. Ac Press, Boston
Bougrier C, Albasi C, Delgenès JP et al (2006) Effect of ultrasonic, thermal and ozone pre-treatments on waste activated sludge solubilisation and anaerobic biodegradability. Chemical Engineering and Processing: Process Intensification 45(8): 711-718
Carlton EJ, Liu Y, Zhong B et al (2015) Associations between schistosomiasis and the use of human waste as an agricultural fertilizer in China. PLoS Neglected Trop Diseases 9(1): e0003444
Carter RC, Tyrrel SF, Howsam P (1999) The impact and sustainability of community water supply and sanitation programmes in developing countries. Water and Environ Journal 13(4): 292-296
Cofie O, Kone D, Rothenberger S et al (2009) Co-composting of faecal sludge and organic solid waste for agriculture: Process dynamics. Water Research 43(18): 4665-4675
Cofie OO, Kranjac-Berisavljevic G, Drechsel P (2005) The use of human waste for peri-urban agriculture in Northern Ghana. Renewable Agriculture and Food Systems 20(2): 73-80
Colón J, Forbis-Stokes AA, Deshusses MA (2015) Anaerobic digestion of undiluted simulant human excreta for sanitation and energy recovery in less-developed countries. Energy for Sustainable Development 29: 57-64
Danso-Boateng E, Holdich RG, Shama G et al (2013) Kinetics of faecal biomass hydrothermal carbonisation for hydrochar production. Applied Energy 111: 351-357
Drewry JJ, Newham LT, Greene RS (2006) A review of nitrogen and phosphorus export to waterways: context for catchment modelling. Marine and Freshwater Research 57(8): 757-774
Escher BI, Pronk W, Suter MJ (2006) Monitoring the removal efficiency of pharmaceuticals and hormones in different treatment processes of source-separated urine with bioassays. Environmental Science & Technology 40(16): 5095-5101
Etter B, Tilley E, Khadka R (2011) Low-cost struvite production using source-separated urine in Nepal. Water Research 45(2): 852-862
Fakkaew K, Koottatep T, Polprasert C (2015b) Effects of hydrolysis and carbonization reactions on hydrochar production. Bioresource Technology 192: 328-334
Fakkaew K, Koottatep T, Polprasert C (2018) Faecal sludge treatment and utilization by hydrothermal carbonization. Journal of Environmental Management 216: 421-426
Fakkaew K, Koottatep T, Pussayanavin, T et al (2015) Hydrochar production by hydrothermal carbonization of faecal sludge. J Water, Sanitation and Hygiene for Development 5(3): 439-447
Ferguson DT (2014) Nightsoil and the 'Great Divergence': human waste, the urban economy, and economic productivity, 1500–1900. J Global History 9(3): 379-402

Franceys R, Pickford J, Reed R et al (1992) A guide to the development of on-site sanitation. Geneva, Switzerland: World Health Organization.
Glibert PM, Harrison J, Heil C (2006) Escalating worldwide use of urea–a global change contributing to coastal eutrophication. Biogeochemistry 77(3): 441-463.
Gold M, Cunningham M, Bleuler M et al (2018) Operating parameters for three resource recovery options from slow-pyrolysis of faecal sludge. J Water, San and Hygiene for Develop 8(4): 707-717
Hanak DP, Kolios AJ, Onabanjo T et al (2016) Conceptual energy and water recovery system for self-sustained nano membrane toilet. Energy Conversion and Management 126: 352-361
Harder R, Wielemaker R, Larsen TA (2019) Recycling nutrients contained in human excreta to agriculture: Pathways, processes, and products. Critical Reviews in Environmental Science and Technology 49(8): 695-743
Hasar H, Unsal SA, Ipek U et al (2009) Stripping/flocculation/membrane bioreactor/reverse osmosis treatment of municipal landfill leachate. J Hazardous Materials 1711-3: 309-317
Heinonen-Tanski H, Sjöblom A, Fabritius H (2007) Pure human urine is a good fertiliser for cucumbers. Bioresource Technology 98(1): 214-217
Heinonen-Tanski H, van Wijk-Sijbesma C (2005) Human excreta for plant production. Bioresource Technology 96(4): 403-411
Hill GB, Baldwin SA (2012) Vermicomposting toilets, an alternative to latrine style microbial composting toilets, prove far superior in mass reduction, pathogen destruction, compost quality, and operational cost. Waste Management 32(10): 1811-1820
Hu M, Fan B, Wang H et al (2016) Constructing the ecological sanitation: a review on technology and methods. Journal of Cleaner Production 125: 1-21
Inglezakis VJ, Poulopoulos SG (2006) Adsorption, ion exchange and catalysis. Amsterdam: Elsevier. 3: 498-520
Jensen PK, Phuc PD, Knudsen LG et al (2008) Hygiene versus fertiliser: the use of human excreta in agriculture–a Vietnamese example. International J of Hyg and Env Health 211(3-4): 432-439
Johnson PT, Townsend AR, Cleveland CC (2010) Linking environmental nutrient enrichment and disease emergence in humans and wildlife. Ecological Applications 20(1): 16-29
Jurado N, Somorin T, Kolios AJ et al (2018) Design and commissioning of a multi-mode prototype for thermochemical conversion of human faeces. Energy Conv and Management 163: 507-524
Koottatep T, Fakkaew K, Tajai N et al (2016). Sludge stabilization and energy recovery by hydrothermal carbonization process. Renewable Energy 99: 978-985
Kwiringira J, Atekyereza P, Niwagaba C et al (2014) Descending the sanitation ladder in urban Uganda: evidence from Kampala Slums. BMC Public Health 14(1): 624
Lalander CH, Hill GB, Vinnerås B (2013) Hygienic quality of faeces treated in urine diverting vermicomposting toilets. Waste Management 33(11): 2204-2210
Lei X, Sugiura N, Feng C, Maekawa T (2007) Pretreatment of anaerobic digestion effluent with ammonia stripping and biogas purification. J Hazardous Materials 145(3): 391-397
Lienert J, Larsen TA (2009) High acceptance of urine source separation in seven European countries: a review. Environmental Science & Technology 44(2): 556-566
Lind BB, Ban Z, Bydén S (2001) Volume reduction and concentration of nutrients in human urine. Ecological Engineering 16(4): 561-566
Liu M, Woudstra T, Promes EJ (2014). System development and self-sustainability analysis for upgrading human waste to power. Energy 68: 377-384
Liu X, Li Z, Zhang Y et al (2014) Characterization of human manure-derived biochar and energy-balance analysis of slow pyrolysis process. Waste Management 34(9): 1619-162

Mehta CM, Khunjar WO, Nguyen V (2015) Technologies to recover nutrients from waste streams: a critical review. Critical Reviews in Environmental Science and Technology 45(4): 385-427

Mkhize N, Taylor M, Udert KM (2017) Urine diversion dry toilets in eThekwini Municipality, South Africa: acceptance, use and maintenance through users' eyes. J Water, Sanitation and Hygiene for Development 7(1): 111-120

Mnkeni PN, Austin LM (2009) Fertiliser value of human manure from pilot urine-diversion toilets. Water SA 35(1):133-138

Monfet E, Aubry G, Ramirez AA (2018) Nutrient removal and recovery from digestate: a review of the technology. Biofuels 9(2): 247-262

Monhol FA, Martins MF (2015) Cocurrent combustion of human feces and polyethylene waste. Waste and Biomass Valorization 6(3): 425-432

Montgomery MA, Elimelech M (2007) Water and sanitation in developing countries: including health in the equation. Environmental Science & Technology, 41:17-24

Nakagiri A, Niwagaba CB, Nyenje PM (2015) Are pit latrines in urban areas of Sub-Saharan Africa performing? A review of usage, filling, insects and odour nuisances. BMC Pub Health, 16(1): 120

Odagiri M, Schriewer A, Daniels ME et al (2016) Human fecal and pathogen exposure pathways in rural Indian villages and the effect of increased latrine coverage. Water research 100: 232-244

Onabanjo T, Kolios AJ, Patchigolla K (2016a) An experimental investigation of the combustion performance of human faeces. Fuel 184: 780-791

Onabanjo T, Patchigolla K, Wagland ST (2016) Energy recovery from human faeces via gasification: a thermodynamic equilibrium modelling approach. Energy Conversion and Management 118: 364-376

Orner KD, Mihelcic JR (2018) A review of sanitation technologies to achieve multiple sustainable development goals that promote resource recovery. Environmental Science: Water Research & Technology, 4(1):16-32

Park JA, Hur JM, Son BS et al (2001) Effective treatment of night soil using anaerobic sequencing batch reactor (ASBR). Korean Journal of Chemical Engineering, 18(4): 486-492

Phaswana-Mafuya N, Shukla N (2005) Factors that could motivate people to adopt safe hygienic practices in the Eastern Cape Province, South Africa. African Health Sciences, 5(1): 21-28

Phuc PD, Konradsen F, Phuong PT (2006) Practice of using human excreta as fertilizer and implications for health in Nghean Province, Vietnam. Southeast Asian Journal of Tropical Medicine and Public Health 37(1): 222

Rahman MM, Salleh MA, Rashid U et al (2014) Production of slow release crystal fertilizer from wastewaters through struvite crystallization–A review. Arabian J Chemistry, 7(1): 139-155

Reed R (1994) Why pit latrines fail: some environmental factors. Waterlines 13(2): 5-7

Ronsse F, Van Hecke S, Dickinson D et al (2013) Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. GCB Bioenergy 5(2): 104-115

Ronteltap M, Maurer M, Gujer W (2007) Struvite precipitation thermodynamics in source-separated urine. Water Research, 41(5) 977-984

Rose C, Parker A, Jefferson B et al (2015) The characterization of feces and urine: a review of the literature to inform advanced treatment technology. Critical Reviews in Environmental Science and Technology, 45(17): 1827-1879

Semalulu O, Azuba M, Makhosi P et al (2011) Potential for reuse of human urine in peri-urban farming. In Innovations as Key to the Green Revolution in Africa. Springer, Dordrecht, p 651-660

Semiyaga S, Okure MA, Niwagaba CB (2015) Decentralized options for faecal sludge management in urban slum areas of Sub-Saharan Africa: A review of technologies, practices and end-uses. Resources, Conservation and Recycling 104: 109-119

Shiming L (2002) The utilization of human excreta in Chinese agriculture and the challenge faced. http://www.ecosanres.org/pdffiles/NanningPDFs/Eng/Luo%20Shiming%2010 C11rev.pdf.
Simha P, Ganesapillai M (2017) Ecological Sanitation and nutrient recovery from human urine: How far have we come? A review. Sustainable Environment Research 27(3): 107-116
Singh S, Mohan RR, Rathi S (2017) Technology options for faecal sludge management in developing countries: Benefits and revenue from reuse. Environ Tech & Innovation 7: 203-218
Snell JR (1943) Anaerobic digestion: III. Anaerobic digestion of undiluted human excreta. Sewage Works Journal 15(4) 679-701
Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R., 2010. A review of biochar and its use and function in soil. In Advances in agronomy. Academic Press p 47-82
Somorin TO, Kolios AJ, Parker A et al (2017) Faecal-wood biomass co-combustion and ash composition analysis. Fuel 203: 781-791
Sonko EH, Mbéguéré M, Diop C (2014) Environmental impact of recycling nutrients in human excreta to agriculture compared with enhanced wastewater treatment. Science of the Total Environment 493: 209-219
Sonko EHM, Mbéguéré M, Diop C et al (2014) Effect of hydraulic loading frequency on performance of planted drying beds for the treatment of faecal sludge. Journal of Water, Sanitation and Hygiene for Development 4(4): 633-641
Sun B, Zhang L, Yang L (2012) Agricultural non-point source pollution in China: causes and mitigation measures. Ambio 41(4): 370-379
Udert KM, Wächter M (2012) Complete nutrient recovery from source-separated urine by nitrification and distillation. Water Research 46(2): 453-464
Van Zwieten L, Kimber S, Morris S et al (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant and Soil 327(1-2): 235-246
Ward BJ, Yacob TW, Montoya LD (2014) Evaluation of solid fuel char briquettes from human waste. Environmental Science & Technology 48(16): 9852-9858
Winker M, Vinnerås B, Muskolus A et al (2009). Fertiliser products from new sanitation systems: their potential values and risks. Bioresource Technology 100(18): 4090-4096
World Health Organization (2017) Joint Water Supply and Sanitation Monitoring Programme, 2017. Progress on sanitation and drinking water: Joint Monitoring Programme 2017 update and SDG baselines. World Health Organization: Geneva.
Yadav KD, Tare V, Ahammed MM (2010) Vermicomposting of source-separated human faeces for nutrient recycling. Waste Management 30(1): 50-56
Yermán L, Hadden RM, Carrascal J (2015) Smouldering combustion as a treatment technology for faeces: exploring the parameter space. Fuel 147: 108-116
Zavala ML, Funamizu N, Takakuwa T (2005) Biological activity in the composting reactor of the bio-toilet system. Bioresource Technology 96(7): 805-812