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Fecal Sludge Recycling to Useful Products: Environmental Concerns, Viability and Potential

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ABSTRACT

Biofertilizer, biogas and the chemical substances in those two, which are generated as a result of several treatment methods fecal sludge (FS) are usually subjected to, can be recovered for diverse applications. The treatment methods are classified into traditional and innovative methods. FS sludge impacts the environment negatively and one of the most adopted methods for its treatment from toilets where they originate, are composting and anaerobic digestion to recover biogas and organic fertilizer. FS potential for biogas production has been critically examined here using literature sources. It is discovered that FS is not largely favored as a means of recovering bioenergy in most parts of the world due to hygiene concerns, even though it is one of the most abundant organic materials for bioenergy recovery through anaerobic digestion. This work hence studied the factors hindering FS recycling and reuse, which it convincingly addresses. The work also demonstrates ways FS can be safely collected and digested to useful products and make a case for future investment in the sector by relevant bodies due to its feasibility, profitability and environmental-friendliness. Implementation of a system that recovers FS from latrines of households and public places and converts them to useful products are therefore recommended.

INTRODUCTION

Human excreta (HE) or fecal sludge (FS) is a mixture of excreta and urine and sometimes referred to as organic waste of human body (OWHB), also containing anal cleansing materials, water and undigested food residues (Anukam & Nyamukamba, 2022; Regattieri *et al*., 2018). It is discharged in toilets where it stays temporarily before its collection for disposal, biological treatment or bioenergy conversion. 'Night soil' is a traditional term used for HE collected in the night to avoid humans getting intimidated by the mention of their own mess (Muthuniranjan & Murugan, 2020; Parab *et al*., 2021). As the population of humans increase, the burden to increase food production grows, and is consistent with the generation of huge volume of excreta (Hadiyarto *et al*., 2020). Almost all cultures across the globe practiced the recovery (sometimes as night soil) and use of HE for agricultural purposes dated back to several millennia (Mkude *et al*., 2021; Nordin, 2010; Timmer & Visker, 1998). This act is favored by its rich organic mineral contents such as lipids, polysaccharides, proteins and chemical elements (Anukam & Nyamukamba, 2022). But currently, there is a huge decline in HE exploitation for crop production, traced to the discovery of modern toilet systems, preference on chemical fertilizer and the fear of exposure to serious health issues (Linares-Lujan *et al*., 2017). Excess hormones, pathogens, nutrients and heavy metals inherent in HE may affect both humans and animals if uncontrollably discharged on the surrounding environment (Lam *et al*., 2015).

Spångberg *et al*. (2021) reported that the human population may likely increase by 35% by 2050, and if meaningful solution to address sanitary concerns connected with HE disposal or reuse is not devised, mankind will continue to face pandemic caused by harmful microorganisms. Perhaps recent direction of HE to aerobic/anaerobic treatment to convert to useful energy (in form of biogas) and biofertilizer is the greatest known solution at the moment. Biogas is a mixture of carbon dioxide (CO_2), methane (CH_4), hydrogen sulphide (H_2S), nitrogen (N_2), water (H_2O), ammonia (NH_3), hydrogen (H_2) and trace elements, that is produced when microorganisms feed on biodegradable materials (e.g., FS) in an oxygen-void environment at a neutral pH and favorable temperature conditions. The semi-solid remain from such process is a digestate that can be used for fertilizer as well as a source to recover other chemical substances. Apart from biogas generation which has been produced from several other organic materials long ago (Ali, 2019; Yaradua & Bello, 2020), HE can be used as fecal char for heat applications

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(Somorin, 2020). Biogas from FS can be used for electricity generation, fuel for transportation and for heating and lighting via a methodology similar to cattle manure biogas system (Andriani *et al.*, 2015). Upgraded biogas or biomethane has less greenhouse gas emissions related to its use and hence there is no excuse for the non-utilization of HE to produce biogas, since FS itself emits NH_3 and CO_2 to the atmosphere. Even though a novel syntropic calcium acetate oxidation (SCAO) bacteria capable of controlling NH_3 and greenhouse gas emissions from FS has been developed by Emetere, *et al.* (2022), it is unwise to ignore its potential for several other uses.

It is predicted that if all HE is explored for recovery of useful products like biogas, organic fertilizer and chemical synthesis across the globe, a lot of profit will be generated – and invariably make a lot of countries address shortages in their energy production. According to Timmer & Visker (1998), excreta production is between 100-520 g/day wet weight while urine production ranges from 1-1.5 L/day. Snell is the first person to publish a study on anaerobic digestion of HE where it was found that 0.5 m^3/kg VS of biogas is contained in diluted FS (Colón *et al.*, 2015; Snell, 1943). The merits of biogas including its ability to replace fuel wood, kerosene, liquefied natural gas, and charcoal for cooking suffices to leave no stone unturn in terms of research, including; on the use of undiluted FS as a potential feedstock (Rao & Gebrezgabher, 2018). Asian countries, especially India and China currently take the lead in biogas and biofertilizer production from HE. In the northern provinces of Vietnam, 85% of the families use excreta as fertilizer in agriculture, while in sub-Saharan Africa, HE production is around 27 million tonnes yearly (Timmer & Visker, 1998; Tu, 2018; Vu-Van *et al.*, 2016). However, majority of countries in Africa still have to rely on non-governmental organizations (NGOs) who render limited and unsustainable support in order to harness this potential. Generally, exploitation of FS for the manufacture of useful products is challenged by lack of technical know-how and acceptability in all parts of the world. Hence, objectives of this work are to highlight hygiene and safety challenges and how to solve them during FS collection, treatment and reuse; draw the attention of researchers to further study the viability of FS for the recovery of useful products by providing a rich background information and; portray this venture as a profitable business capable of addressing energy and food production needs of the human race.

LITERATURE REVIEW

Environmental Safety Concerns, Excreta Collection and Treatment

Risks Posed by Poor Excreta Management

Destination and status of feces are the main concern after it has been released by humans via the use of toilets or restrooms. Where provisions for toilet facilities are not made, humans make natural use of solitary environments like bushes, riverside and forest to pass-out excreta. The former (toilet use) is a controlled method of disposing off human feces while the later has the potential of causing serious health implications. Nevertheless, analogy of sanitary measures put in place for HE in developed and developing countries are different. By regions, Bao (2006) reported that sanitary coverage is 49% in third world countries and 98% in rich and developed nations. In addition, 95% of sewage are discharged freely (untreated) into water bodies (coastal area, lakes, rivers, etc.) in developing cities of the world (Jewitt, 2011). Generally, based on Triastuti *et al.* (2016) reports, 3.4×10^6 kg of HE and 34×10^3 m^3 of urine are discharged to water bodies per day. When carefully examined, those assertions may be true, as Colón *et al.* (2015) and Agani *et al.* (2016) previously mentioned that about 2.5 billion people are without improved sanitation in 2014 alone out of which 1 billion practiced open defecation. A 50.6% decrease to 494 million people practicing open defecation occurred from 2014-2020 of which 23% is in Nigeria, 25% Haiti, 45.15% Togo, 14.93% India, 69% Chad, 0.22% South Africa, 2.58% Burundi, 33% Ethiopia, 0.32% China, 5.55% Cameroon, 16.07% Tanzania, 68.11% Niger, 2% Senegal, 9% Indonesia and 3% Philippines (Blackett *et al.*, 2014; Inah *et al.*, 2023; Shukla *et al.*, 2023). From the investigations, Sub-Saharan Africa, Oceania and Southern Asia are the most vulnerable regions as a result of a very low sanitation coverage of 30%, 35% and 42% respectively (Agani *et al.*, 2016). Hence, finding solutions to HE disposal challenge (Patiya, 2009) must be prioritize by all human beings being the main recipients of failure consequences.

Every individual produce 0.13-1.5 kg of feces and 1.5 L of urine daily (Ali, 2019; Muralidharan, 2017; Oseo-Marfo *et al.*, 2022; Regattieri *et al.*, 2018; Ronteltap *et al.*, 2010), divided into 25 wt% dry solids (32.5–375 g/person/day) and 75 wt% water (Mara & Cairncross, 1989; Somorin, 2020; Zseni & Nagy, 2016). On a per capita basis, Somorin (2020) reported a range from 15 – 1505 g/cap/day for an average healthy adult while for China and Kenya respectively (Maurya, 2012), as minimum as 69 g/capita/day and a maximum of 520 g/capita/day are generated in their country. Still, quantity, appearance, chemical and physical characteristics of HE produced are functions of the individual's eating habits, dietary intake (food and liquid consumed), ethnicity, geographical location, age, gender, economic status and health conditions (Muthuniranjan & Murugan, 2020; Regattieri *et al.*, 2018; Saydullaeva, 2023; Somorin, 2020) which makes their composition differ per person, per region, and per day according to Ronteltap *et al.* (2010). Ultimately, the frequency and volume of reckless disposal of fresh HE on the environment are typified as a serious health problem that must be addressed – particularly, those connected with microbiological and chemical contaminants causing unpleasant smell, ground and surface water pollution and spread of excreta-related infections (Hossain *et al.*, 2015; Nzouebet *et al.*, 2022). In essence, the bladder of a healthy person contains sterile urine but detrimental to him/her and his/her fellow human beings after excretion (Spångberg *et al*., 2021). One major environmental pollution concern is the propagation of diseases by HE containing millions of disease-causing microorganisms (Reed & Shaw, 2003; Zhong-Xian *et al*., 1982). A common pathogen called *Salmonella typhi*, originating from night soil is the most destructive and can survive for a very long time (Parab *et al*., 2021). In Ghana, 41 million diarrhea cases causing 7300 deaths was a result of poor FS handling in 2017 while 600,000 deaths of children worldwide, according to Bill and Melinda Gates Foundation, was a result of contamination of food and water with fecal matter (Adjama *et al*., 2022; Agani *et al*., 2016). The hygiene-deficit disease is top 10 killers in Philippine right now as Holmer & Itchon (2008) reveals that 8 million Filipino children suffer from intestinal parasites as a result of nonexistence of functional sanitary facilities both at school and at home. Therefore, several measures needs to be put in place at appropriate locations to properly collect, use or dispose of HE, especially during its application as fertilizer (Spångberg *et al*., 2021). Sanergy, Sulabh and TOSHA 1 are organisations currently helping with the management of HE in their host communities (Gebrezgabher *et al*., 2017; Jha, 2005; Likoko, 2013).

Approaches to Excreta Collection

HE eventually gets naturally combined with anal cleansing water, stormwater, flush water, toilet paper, condoms, flushed secret items, vomits, domestic and industrial used water, blamed at human activities both at home and in the environment, which makes its collection as sole waste material difficult (Harder *et al*., 2019). The bottom-line is, ease of HE collection is still tied to the availability of adequate toilet facilities at strategic location for home and public use (Figure 1a) as well as the willingness to use them by people who might prefer open-urination under trees, house backyard fences and drainage lines. A latrine is a basic sanitation facility that is used for the disposal of human waste. It is a simple, often temporary structure that is typically used in rural or low-income areas where access to more advanced sanitation systems may be limited. Latrines can be constructed in a variety of ways, such as using a pit dug into the ground, or using a simple structure with a hole in the ground and a seat or platform for sitting. In Kass South Darfur, Sudan, Wini *et al*. (2020) puts the average number of communal latrines users at 50:1. Thirty million people out of more than 80 million Nigerians living in rural areas adopted the latrine system (Emetere & Adesina, 2019). To sum it all, 650 million people in sub-Saharan Africa, 800 million Indians and generally, one-third of the world lacks proper sanitation (Barani *et al*., 2018; Mukherjee & Chakraborty, 2016). Globally, 2.7-3.4 billion people in poor communities (especially Southeast Asia) relied on pit latrines or unsewered sanitation systems which causes the most pollution among all toilet systems as pathogens may percolate into the groundwater (Hafford *et al*., 2019; Harper *et al*., 2018, 2020; Odey *et al*., 2019). Sklar *et al*. (2019) and Zewde *et al*. (2021) estimated a rise in sewered systems, septic tank or pit latrines use to 4.9-5 billion people by 2030. Foremost types of sanitary latrines used in China are the double urn funnel-pan latrines, biogas-producing latrines, and the three-compartment tank latrines (Wei *et al*., 2009).

Latrines can be either "dry" or "wet". Wet latrines are designed to collect both solid and liquid waste, which is then allowed to decompose over time. The invention of the flush toilet tank was recorded by Joseph Bramah in 1788 (Zseni & Nagy, 2016). Dry latrines, on the other hand, are designed to collect solid waste, which can then be periodically emptied and disposed off. Composting toilets such as bio-toilets are referred to as dry latrines, as they do not need water (Somorin, 2020). Aerobic microorganisms in bio-toilets are responsible for decomposing fecal organic matter to useable form (called compost – containing N, P & K) via its composting chamber equipped with heater, mixer and exhaust fan; and the release of CO_2 and water to the air (Triastuti *et al*., 2016). As contained in Maqbool *et al*. (2022), approximately 83% of households in Pakistan utilize the flush toilet facilities out of which 17% have pit latrines, 18% have open drains, 21% have septic tanks and 27% are linked to sewerage. Ersson & King (2019) reported that from 1999-2012, 75% of fresh toilets installed in China were water flushed; touted as the most common modern toilet, where they further highlighted their deficiency including energy, portable water and capital intensiveness. Because flush toilets are water intensive, the use of a urine-diversion dehydration toilet (UDDT) will not only separate the liquid from the solid fecal matter, but also allow the recovery of nutrient-rich solid for safe fertilizer production (Holmer & Itchon, 2008; Kooij *et al*., 2020). Pit latrines are hence the most profitable scheme of collecting, storing and treating of excreta in many developing countries in periods of heightened water shortage (Joveniaux *et al*., 2022; Madikizela *et al*., 2017; Rahman *et al*., 2016). A survey report by Triastuti *et al*. (2016) indicates that, high volume of water (average of ±10 L) is needed to flush toilet bowl and clean the body in Kiaracondong sub district, Bandung city, Indonesia. Latrines are emptied by manual (using buckets) or mechanical means, using emptying equipment (gulper, cesspool and Rama) (Madikizela *et al*., 2017; Simiyu *et al*., 2021; Singh *et al*., 2022; Sklar *et al*., 2019). Across continents, manual emptying (Figure 1c) is predominantly practiced in Africa and South Asia while mechanical emptying (using vacuum trucks) is frequently carried out in the Caribbean, East Asia and Latin America (Peal *et al*., 2014). In low-income countries, emptying pit latrines is still a major challenge, according to Buxton & Reed (2010) and Hossain *et al*. (2015).

In order to channel HE to variety of uses including fertilizer, biogas and energy generation, a strategic method of collecting the waste (e.g., Figure 1c) must be put in place. As an example, Sulabh, an Indian international social

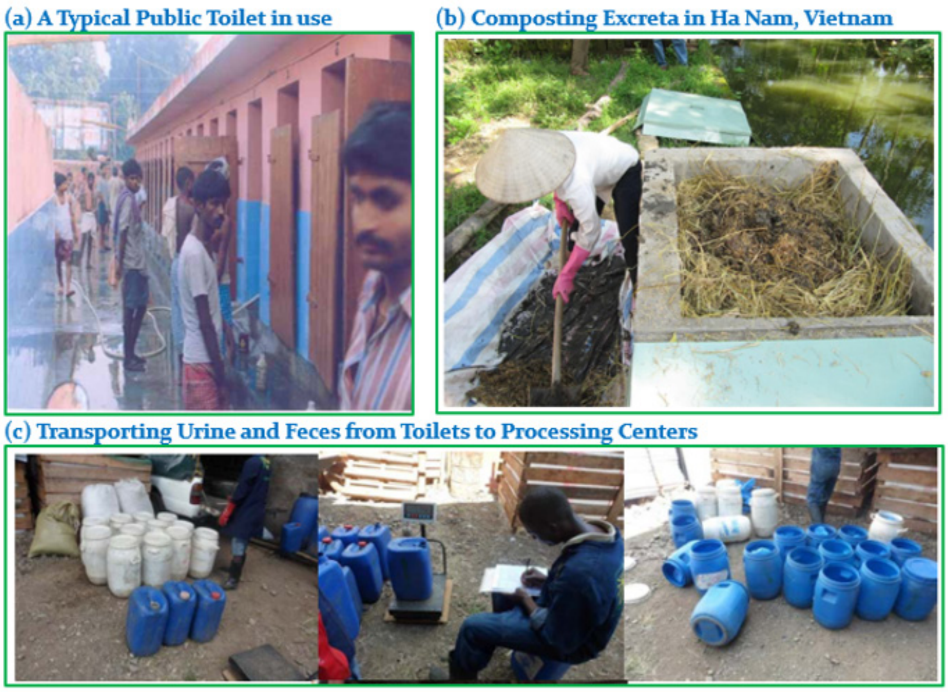

Figure 1: Human Excreta Collection and Treatment (Jha, 2005; Likoko, 2013; Tu, 2018)

service non-governmental organization (NGO) through their institute of technical research and development, built a cheap, easy-to-construct, environmentally-favorable and socio-culturally-acceptable toilet at domestic and public level (Gebrezgabher & Natarajan, 2017; Jha, 1984). Part of their goal is to enhance environmental sanitation and create jobs by constructing over 6000 public toilets on "pay and use" basis in slums, bus stands, markets and hospitals (Jha, 2005). The institute through this gesture was able to liberate more than 60,000 scavengers embarking on manual emptying of human 'nightsoil' from buckets and latrines. Ninety to 95% of the people scavenging for HE described as the most degrading, stigmatizing and dirty jobs in the world are women, sometimes earning as little as 1-50 Indian Rupees ($0.012-0.61) per pit per day (Gebrezgabher & Natarajan, 2017; Lane, 2008; Simiyu *et al.*, 2021). Such NGOs, usually take advantage of refugee camps, public transport stations (e.g., railway and bus stations), prisons and markets where people might be largely concentrated, as the main targets to site toilets for collecting HE or FS. Previously, Ali (2019) suggests the collection of fecal matter from refugee camps using septic tanks of varying sizes. Namely, a tank capable of holding 5 days of HE of 150 individuals (weighing between 225-250 kg), another tank of capacity ranging from 750-800 kg to collect 5 days fecal matter of 500 people, and an underground septic tank which he described as infeasible because it is temporary. It is estimated that if 520 refugees in the camp passes 300g each of feces daily, then around 150 kg/day of FS will be realized to generate compressed biogas and manure for agricultural lands.

Treatment Technologies for Safe and Sustainable Excreta Management

Need for save disposal and reuse of FS after its treatment is necessary and has been stressed severally. Methods of treating HE can be categorized into three, namely discharge (to septic tank, soil or water body), manure use and biogas use (Ying *et al.*, 2014). Traditional methods and technologies for HE treatment includes storage, dehydration and composting (Figure 1b), whereas innovative methods and technologies for its treatment are insect assisted composting, anaerobic digestion, fermentation, thermal decomposition, electromagnetic radiation, microbial electrochemical technologies and chemical treatment for stripping and precipitation of nutrients, stabilization and disinfection (Kelova & Jenssen, 2018). Almost all FS treatment approaches (viz., physical or chemical method) inactivates harmful microorganisms in the waste. They are ozonation, lactic acid fermentation, UV irradiation, sand drying, chlorination, lime stabilization, co-composting, anaerobic digestion, use of wood ash, biocides, peracetic acid, hydrogen peroxide, performic acid and NH_3, which are characterized under traditional and innovative techniques (Loiko *et al.*, 2023). Advantage of lime addition (known to alter pH levels in the waste) kills deadly pathogens by acting as a biocide, but in turn reduces total Kjeldahl nitrogen concentrations and soluble phosphate, making the sludge low quality for use as biofertilizer (Lindberg & Rost, 2018; Zewde *et al.*, 2021). Ammonia does the same but is lost due to ventilation, which explains the reason why NH_3 is high in pits without flush water and less in pour flash latrines with flush water. Peguero *et al.* (2021) explains the microbial safety and how heat-treated FS may be favorable for black soldier fly larvae production.

Method of operation employed by the Sanergy's model from Sanergy Organization is a typical example of innovative model of dealing with HE in densely populated urban areas (Likoko, 2013). Several other community-based organizations (CBO) are keying into sanitary toilet sludge treatment to reap income for deserving communities through its conversion to useful end-product and a way of ensuring environmental protection. Viz., with the support of Umande Trust in Kenya, a CBO known as TOSHA 1 implemented a bio-center in form of toilets used by around 1000 people daily in Nairobi (settlements of Kibera) to collect, treat and convert FS to biogas (Gebrezgabher *et al*., 2017). The development of thermal treatment systems has been fast-tracked through the Bill & Melinda Gates Foundation's Reinvent the Toilet initiative (Rowles *et al*., 2022). Rahman *et al.* (2016) reported the establishment of an FS treatment plant by Lakshmipur Paurashava, funded by the Government of Bangladesh (GoB) and the Asian Development Bank (ADB) and runned by the Department of Public Health Engineering (DPHE) with the support of Secondary Town Water Supply and Sanitation Sector project. Paurashava empties FS collections mechanically at Tk. 500-1000 per pit. Where biogas is desired, anaerobic digestion amongst other treatment method might require separate collection of urine and feces through the construction of special toilets called UDDT, that uses a rear bowl for feces and a front bowl for urine (Kooij *et al*., 2020).

This separation is known as FS stabilization, done prior to its treatment, where the liquid portion is passed for treatment using wastewater treatment plant and the solid part are treated to make it fit for agricultural reuse or disposal (Zewde *et al*., 2021). Since studies on dewatering performance of FS are limited, there is need for further studies by applying techniques like thermal pre-treatment or drying and solar dehydration (Bhakta, 2022; Bourgault *et al*., 2019; Sklar *et al*., 2019). Studies by Junggoth & Kuster (2020) shows that dewatering of FS using sand drying beds is already common in rural Thailand. Essentially, Bousek *et al.* (2018) proposed the building of a field laboratory for monitoring FS treatment plants, most likely to routinely test their efficiency.

Energy and Biofertilizer Recovery

Energy recovered from organic matter may be referred to as bioenergy. Decomposing HE aerobically or anaerobically generates biogas which can be used for cooking, fuel for transportation, heat and electricity generation. A good biodegradable material such as FS is made up mainly of food residues, pathogens (e.g., viruses, eggs of helminths, fungi, bacteria and cysts of protozoa), plant-essential nutrients (e.g., inorganic salts & mineral elements like mercury, copper, manganese, calcium, barium, iron, zinc, lead, phosphorus, potassium, magnesium, nickel and cadmium), water and energy (Appiah-effah *et al*., 2015; Deka *et al*., 2022; Edith *et al*., 2013; Maurya, 2012; Nordin, 2010). The microorganisms, especially *E. coli, Salmonella typhii, Campylobacter, Enterobacter agglomerans, Candida sp*., Norovirus, Rotavirus,

Figure 2: HE Anaerobic Biogas Production and Farmland Application of Effluent (Emetere, Chikwendu, & Afolalu, 2022; Holmer & Itchon, 2008; Rwigema, 2019)

Cryptosporidium and Giardia commonly detected in feces samples, depending on different stages of the decomposing of the FS, are responsible for methane or biogas production (Astuti *et al.*, 2016; Harder *et al.*, 2019). HE contains 15-30% (or 350g) dry solids and thus, its aerobic/anaerobic digestion will require no addition of water due to sufficiency provided by its urine constituent that is itself made of 90% water as released from humans (Harder *et al.*, 2019; Mara & Cairncross, 1989; Maurya, 2012). Cumulatively, biogas is generated optimally if the FS sample use contains sufficient amount of nutrients and water to enhance the role played by microorganisms. However, the length of time at which the biogas product is realized in this case depends on viable pathogens still present in the FS housed by a bioreactor overtime.

For instance, since *Salmonella typhii*, can survive for 6 weeks in an anaerobic environment, a hydraulic retention time (HRT) of 45 days may be allowed to generate a pathogen-free effluent (Figure 2b) which may be detrimental to the environment if applied on land to grow crops (Parab *et al.*, 2021).

Biogas production effluent from FS or the digestate is rich in nutrients and may serve as fertilizer (Figure 2c-d) comparatively with chemical fertilizer for crop production (Patiya, 2009; Spångberg *et al.*, 2021). Ancient people make significant use of HE to maintain soil fertility and organic soil amendment for more than 4000 years before the advent of sewer networks, water closets and currently the widespread use of synthetic fertilizer bringing this practice to a very minimum (Harder *et al.*, 2019; Mara & Cairncross, 1989). Though, presently in Southeast Asia, this has been intensively practiced for crop cultivation in countries including Vietnam, Timor Leste, Thailand, Singapore, Philippines, Myanmar. Malaysia, Laos, Indonesia, Cambodia and Brunei (Lam *et al.*, 2015; Pham *et al.*, 2016). Nevertheless, as mentioned earlier, care must be taken to run away from the risk of disease-infection through harmful microorganisms inherent in either the digestate from HE anaerobic treatment or FS directly collected from toilets, if they must be used on agricultural lands. Fertilizing crops with untreated FS or digestate of HE digestion causes helminth, tapeworm, intestinal nematode, schistosomiasis infections both by field workers, crop consumers and animals (Agarwal *et al.*, 1978; Mara & Cairncross, 1989; Pham-Duc *et al.*, 2013). Notably, Owamah *et al.* (2014) discovered the presence of Klebsiella, Pseudomonas, Clostridium, Bacteroides, Bacillus, Penicillum, Aspergillus and Salmonella in the digestate after co-digesting HE with food waste (FW), where it was found that the residual total coliforms (2.10×10^{8} CFU/mL) in the digestate was above acceptable limits for straight application on farmlands. Though, according to Appiah-effah *et al.* (2015), the range of bacterial load in fresh FS before anaerobic digestion is $0.2\times10^{6} - 4.5\times10^{7}$ CFU/100 mL.

On the other hand, biogas, a co-product of the anaerobic treatment process after upgrading to biomethane to generate energy had little/no effect to consumers compared to biofertilizer – because biomethane have less green-house gas emissions associated with its use. A medium to produce biogas from FS (biodigester – Figure 2a) can be a plastic bag, bottle, metallic container or a plant built with reinforced concrete cement for small- and large-scale biogas production. Normally, the volume of the biogas generated is measured using the water displacement method and can be stored using a gas balloon or a liquid displacement chambers in large plants (Hadiyarto *et al.*, 2020; Jha, 2005). In the literature, 0.1-0.4 kg of HE with a pH range of 4.6-8.4, 77% water and 23% dry matter is said to generate 0.35-0.5 m^3/kg (or 0.02-0.028 m^3/kg dry waste) of biogas (Adjama *et al.*, 2022; Andriani *et al.*, 2015; Mudasar & Kim, 2017). Since the CH_4 content in biogas characterizes its ability to mimic natural gas property, compositions of 65-66% CH_4, 32-34% CO_2, 1% H_2S and traces of N_2 and NH_3 in a HE-based biogas, as reported by Jha (n.d.), is enough to recover energy for various applications. Around 5200-5900 kcal of energy can be generated from 1 m^3 of biogas, enough to boil 130 kg of water originally at 20℃ or light a biogas lamp with a brightness of 60-100W for 5-6 h (IDRC-TS8e, 1978). As regards FS, number of people generating excreta at home or public toilet complexes (Pathak & Jha, 2023) will determine the amount of HE generated, gas produced and the potential energy that can be recovered. As estimated by Ali (2019), a refugee camp containing 10 million people can output 388.8 billion kcal energy or 0.0927 billion kWh electricity. In that case, around 7 billion people in the world right now, can produce near 14 million tonnes of feces daily and invariably leads to the generation of 160,000 MW of energy (Haruna *et al.*, 2016). Based on this merit, the same author reports a plan to realize 500 kW from each of the 20 installed HE power generating plants in Rwanda at prisons, to take advantage of thousands of prisoners sentenced for massacres. Likewise, a project worth $1.5 billion was previously sponsored by Bill and Melinda GATES foundation in Ghana to utilize HE for domestic power generation. FS qualifies as a fuel because of its characteristic volatile matter content ranging from 39-50% and a mean calorific value of 17.3 MJ/kg dry solids (Saha *et al.*, 2022; Sayem, 2022).

METHODOLOGY

After describing the energy and biogas recovery from FS, the treatment technologies for its safe and sustainable management, collection approaches and risks posed by its poor management, methods or techniques previously used in promoting FS biogas technology was described using literature sources. The influence of nutrient content availability in the feedstock and the potential recovery of other chemicals was vividly explained.

Promotion of HE Biogas Technology

Being a means to safeguard the environment from pollution and potential health challenges accompanying FS or HE generation, disposal and conversion, the biogas technology is gradually being keyed-into by several individuals, organizations and government authorities (Likoko, 2013). In their work, Emetere & Adesina (2019) endorses the adoption of a vigorous sewage sludge (SS) system to augment HE biogas production at homes. Though, before now, China and India applies a domestic-scale biogas production system making use of pig manure, cattle dung and HE (Zwart & Langeveld, 2010). Due to technical expertise, HE is particularly hard to deal with in Africa and is slowly being introduced in the continent; especially in Nigeria, Kenya and Rwanda (Emetere *et al.*, 2021; Zwart & Langeveld, 2010). To maintain public health and safety and ensure a clean environment, Onwosi *et al.* (2022) proposed a cost-effective decentralized anaerobic digestion (DAD) scheme, feasible for the Nigerian HE management system. In the country, Nayem (2023) reported that estimates of biogas derived from HE is around 2.6 billion m^3/yr – equivalent to 57.2×10^9 MJ of energy annual generation. While in Nairobi, Kenya, TOSHA 1 is the only notable implemented project by an NGO to convert feces of 600-800 people per day in a biodigester to biogas (Gebrezgabher *et al.*, 2017; Mumbi, 2017). TOSHA 1 is a bio-centre having toilets, showers, meeting hall, operator's office, restaurant and a 54 m^3 fixed dome digester made of bricks. The International Committee of Red Cross (ICRC) in partnership with local organizations in Philippines, Nepal and Rwanda, constructed biogas plants to limit the cost associated with the utilization of fossil fuels and firewood in prisons of those countries (Rao & Doshi, 2017; Rwigema, 2019). The plant utilizes kitchen waste and HE to generate biogas. This gesture further draws the attention of subscribers to the biogas technology, of a new site to construct biogas plants to exploit the human waste released in a people-concentrated area like prisons, where there are currently more than 11.5 million prisoners worldwide.

Bangladeshi government had previously planned to establish a biogas plant targeting HE of 103,200 Rohingya refugees in Bhashan Char Island to produce 3054 m^3 of biogas per day (Mawla *et al.*, 2021). India remains

Table 1: Biogas Produced from Mono- and Co-digestion of Human Excreta with Other Materials

Author	**Feedstock**	**Digester**	**Operating Condition**	**Feed Amount**	**Biogas; Biomethane; Methane**
(Parab *et al.*, 2021)	HE + KW	Malaprabha digester Model	Grinded Feed; pH = 6.5-7.5	200 g/day HE & 200 g/day KW	5.4 minutes of combustible gas
(Colón *et al.*, 2015)	Undiluted HE	17 L Floating Dome Anaerobic Digester	Constant Temperature = 30°C; HRT = 40 days; and batch feeding	120 g wet feces and 300 mL urine	0.44 NLbiogas g^{-1} COD
(Hadiyarto *et al.*, 2020)	CW + HE + Inoculum/ microbe (Activated sludge of CD and feces)	5 L Biodigester	C/N ratio = 30; pH = 7.6; RT = 42 days; and Ambient tempe = 25-35°C	-	485±10 mL/day
(Owamah *et al.*, 2014)	FW + HE		RT = 60 days & Temp = 22-31°C	(12 kg FW & 3 kg HE) or 30 L slurry (Feed : Water = 1:1 w/v)	
(Hien *et al.*, 2014)	VW + HE		RT = 60 days	(1) VW:HE = 2:1 (2) VW:HE = 1:1	
(Singh *et al.*, 2021)	HE + PL + CD	5 L Reagent Bottle	SRT = 52 days; Room temp = 25-35°C	Separate digestion each of 2kg feed: (1) 100% HE (2) HE:PL = 1:1 (3) 40% HE & 60% CD 4L slurry (Water:Feedstock = 1:1 w/v)	(1) 7.62×10^3 mL (2) 9.85×10^3 mL (3) 12.96×10^3 mL
(Rathamuang *et al.*, 2015)	HE	120 mL Serum Bottle using UASB	Temp = 37±1°C; RT = 60 days	70 mL	8 mL

(Edith *et al.*, 2013)	ME, HU & CD	186 L Barrel	Temp = 25-35.4°C; pH = 3.7-10.29	(1) 124L ME (2) 70L ME + 54L HU (3) 70L ME + 54L HU + 5kg CD	(1) 21.13 dm^3 (2) 827.04 dm^3 (3) 601.95 dm^3
(Song *et al.*, 2012)	HE (9.1% DM), CD (18.5%) & WS powder (95.8%)	5 L Plastic pot with Temperature controller	Different temperature (15, 20, 25, 30°C)	(1) 1665g HE + 335g Water (2) 832g HE + 409g CD + 759g Water (3) 832g HE + 515g WS + 807g Water	At 30°C: (1) 86.89 mL/g (2) 99.13 mL/g (3) 113.45 mL/g
(Jahan *et al.*, 2022)	FS + Microalgae	200 mL Multi-batch reactor	C/N ratio = 9.6 Microalgae & 27.3 FS; HRT = 18 days; Temp. = 30°C	50:50 Mixing Ratio	281 mL/gVS
(Makinde, 2023)	Liquid Human Manure	6 m^3 Fixed dome plant	RT = 20-40 days & Temp = 18-43°C	438 m^3/yr (1.2 m^3/day)	2.4 m^3/day biogas & 40 litres/day of fertiliser
(Aljbour *et al.*, 2021)	Domestic SS + FW	4 L Dark Glass Bottle	pH = 3.4-6.6 & Temp = 35°C	(1) 100% FS (2) 50/50 Mixed Feedstock	25 mL gas/week (1) 299 mL/g TVSadded (2) 458 mL/g TVSadded
(Krou *et al.*, 2021)	FS + Fermentable Fractions of Solid Waste	Biogas Production Device	RT = 42 days	1 L of co-substrate (2258 tons/DM biomass/yr)	44476 m^3 biogas/yr
(Bhakta, 2022)	Microalgae + FS	Sealed Small Reactor Bottle	HRT = 18 days & Temp = 37±3°C	75 mL Sludge & 75 mL Microalgae	20 mL/gVS 282 mL/gVS CH_4
(Malimi *et al.*, 2023)	FS + FW + Biochar	1 L Bottle Digester	RT = 30 days; pH = 7.2 & Temp = 25.6°C	15 g/L Biochar (0.15mm) + 200g FW + 400g FS	396 mL/gVS
(Burka *et al.*, 2021)	FS + SS + CM + PM	500 mL Sealed vessel (Flask)	Temp = 55°C & RT = 14 days	Ratio = 1:1 (1) FS + SS + CM + PM (2) FS + PM (3) FS + CM (4) FS + SS	(1) 18 mL/g (2) 28 mL/g (3) 22 mL/g (4) 25 mL/g
(Afifah & Priadi, 2017)	FS + FW + GW	51 L Lab-scale Batch reactor	RT = 42 days	1:1:1	0.3 m^3/kgVS
(Dahunsi & Oranusi, 2013)	FW + FS	40 L Lab-scale digester (Karki's model + Floating gas holder system)	Temp = 22-30.5°C; pH = 4.53-6.1 & RT = 60 days	Feedstock C/N = 139:1	84750 cm^3 (58% CH_4, 24% CO_2)

(Gohil *et al.*, 2018)	HE	5 L Lab-scale glass digester	Ambient temp = 20-37℃; RT = 99 days & Feeding mode: Batch and Continuous	6% TS HE	Batch = 322.78 mL/day (68% CH_4) & Continuous = 383 mL/day (67.4% CH_4)
(Duojiao *et al.*, 2017)	HE	400 m^3 CSTR	HRT = 54 days & Temp = 38±1℃	1633 kg/day (OLR = 0.56 kgVS/m^3 day) & TS = 3.5%	145±10 m^3/day biogas & 471±17 m^3 CH_4/t VS

FW = Food waste; HU = Human urine; VW = Vegetable waste; GW = Garden waste; PL = Poultry litter; PM = Poultry manure; CD = Cow dung; CM = Cattle manure; CW = Corncob waste; KW = Kitchen waste; SS = Sewage sludge; ME = Manioc effluent; WS = Wheat straw; DM = Dry matter; TS = Total solids; VS = Volatile solids; TVS = Total volatile solids; RT = Retention time; HRT = Hydraulic retention time; SRT = Solid retention time; OLR = Organic loading rate; NL = Normal litter; UASB = Upflow Anaerobic Sludge Blanket; CSTR = Continuous Stirred Tank Reactor

the highest promoter of a biogas technology utilizing FS. In India, Kumar (2013), discusses the possibility of welding bio-toilets to all 53,000 passenger coaches to improve sanitation in the trains and also generate biogas, by taking the advantage of the Indian Railways carrying 20 million passengers daily. And in over 26 states in the country, flushed HE in 200 pay-and-use public toilet complexes developed by Sulabh is used to produce biogas by channeling the excreta to a biogas plant made up of reinforcement concrete cement (Gebrezgabher & Natarajan, 2017; Jha, 2005). Also, in Dehu village, Pune, India, Dr. S. V. Mapuskar developed the Malaprabha digester technology in 1980; in which a toilet is linked to a digester to convert HE to biogas (Parab *et al.*, 2021). A different technology explained by Forbis-Stokes *et al.* (2016), is the Anaerobic Digestion Pasteurization Latrine (ADPL) where the biogas generated is further used to pasteurize the digester effluent at 65–75℃ to obtain a safe by-product for reuse as fertilizer. Although, several implementations of the biogas technology target only HE at various points of release, the feedstock can be co-digested not only to supplement HE deficient nutrients like carbon-to-nitrogen (C/N) content, but also to augment the excreta if produced in limited amounts. For example, an explanation of the nitty-gritty of municipal solid waste (MSW) co-digestion with HE by Gashaw (2014) as well as FS co-digested with cow dung (CD), cow intestinal waste and mixed organic waste by Soyingbe *et al.* (2019), may guide a successful biogas production process. Table 1 also shows the potentials of biogas production from diluted, undiluted and co-digested HE.

In the literature, enhancement of biogas production using plant seed-based bio-coagulant and iron powder supplementation were illustrated (Agani *et al.*, 2016; Dhungana *et al.*, 2019; Dima *et al.*, 2023). FS digestate can be used to enhance tetracycline removal from soil microbial fuel cells, based on study carried out by Cui *et al.* (2022).

Influence of Nutrient Content Availability and Potential Recovery of Other Chemicals

Component gases in biogas as well as the metallic nutrient content of biofertilizer obtained via anaerobic digestion of HE can be extracted. Immediately HE is discharged and it began flowing through the sewage pipe, it begins to deteriorate – thereby losing its original organic content (Zseni & Nagy, 2016). As such, nutrient composition (e.g., phosphates, nitrates, magnesium and calcium) differences can be observed between the fresh excreta, digestate, compost and vermicompost derived from HE (Moya *et al.*, 2019; Nsiah-Gyambibi *et al.*, 2021). Therefore, the percentage of constituent gases in biogas may differ from time to time in addition to corresponding changes in the metallic element content of the effluent. Issah & Salifu (2012) found out that after anaerobic digestion, ammonium-nitrogen (NH_4-N) in the effluent of HE increased by 25.2%; total phosphate (P_2O_5) increased by 1.7%; total potassium (K_2O) increased by 2%; and heavy metals such as zinc, lead cadmium remained unchanged and in traceable amount (Issah & Salifu, 2012). Approximately 25% of phosphorus from HE in Europe finds their way into soils for food production, according to Kooij *et al.* (2020). HE contains low C/N ratio ranging from 6-15 and is unsuitable for biogas production unless diluted (Andriani *et al.*, 2015; Hadiyarto *et al.*, 2020). Excreta having low C/N ratio will inhibit anaerobic digestion, thereby accumulating high amount of volatile fatty acid and ammonia resulting in low biogas yields (Colón *et al.*, 2015; Sun *et al.*, 2017). In that case, C/N must be kept at 25-30 for an efficient biogas recovery from HE. All the compositions in both HE digestate and the biogas itself can be synthesis. Namely, CO_2 and NH_3 can be recovered from biogas while phosphorus, NH_3 and nitrogen can be recovered from the digestate by subjecting them to series of treatment and methods.

RESULTS AND DISCUSSION

One of the sole aims of this work is to study the viability of FS for conversion into various useful materials and also drive people into its exploitation by suggesting safe and practical approaches to its utilization.

Hinderances and Public Acceptability

Excreta is the dirtiest waste generated by humans. People are still faced by disease infection problems due to its unsafe disposal practices in the developing world. So, advocating for its use in whatever way might not only be frightening to many but could be seen as an uncivilized act. Thus, in some urban settings where majority are least educated about the potentials of HE for energy generation, will outrightly reject any bid to handle excreta for any venture. It is therefor considered a business for scavengers and the poor members of the society (mostly in Africa and Asia) (Rahman *et al.*, 2016). Especially, in Dhaka City where the absence of fecal matter designated site for treatment/disposal contributed to FS emptying in nearby sewer (through manholes), surface drains or low-lying areas; and also Thailand where 70% of untreated FS from septic tanks and cesspools end up in farmland, landfills and waterways (Junggoth & Kuster, 2020; Rahman *et al.*, 2015).

To clear this misconceived feelings and make the technology have widespread acceptability, HE exploitation must be proved to have benefits to the society with no public health risk (Ajieh *et al.*, 2021; Jha, 2005). This must be done in institutions of learning first, especially to generate electricity for hostels and sufficient gas for cooking. Shedrack (2018) hitherto assessed factors influencing acceptance and usage of HE as alternative energy source for cooking in some educational establishments in Bagamoyo District of Tanzania. Likewise in the Niger Delta area of Nigeria, based on Claribelle *et al.* (2020)'s report, a total of 35m^3 of biogas (22.75m^3 biomethane) equivalent to 5.21 kW of power was produced daily to serve 696 students living in hostels at Federal University of Technology, Owerri (FUTO) with electricity from a biogas plant.

Despite the fact that nutrient/fuel prices, project lifetime and transport distances are factors that may influence the smooth running of the process, biogas systems are highly profitable (Schroeder, 2011). According to studies, if all HE produced around the corners of the world are channeled into biogas production, then between $1.6-9.5 billion would be realized, in addition to an amount of electricity that is sufficient for 138 million homes (Haruna *et al.*, 2016; Tu, 2018). Also, the absence of enough electric vehicle charging station in Bangladesh can be resolved by generating electricity through biogas for electric vehicles charging by employing MSW and HE (Alam *et al.*, 2021).

Limited adoption of the biogas system for treating FS will be a thing of the past, if a viable market and business models along the FS management service chain right from toilet provision to emptying/collection and transport to treatment and reuse are developed (Andriessen *et al.*, 2023; Blackett *et al.*, 2014; Harper *et al.*, 2018; Odey *et al.*, 2019). The model must therefore encompass, septage collection vehicle and safety equipment to protect against poisonous gas formation/exposure during clearance as well as a legal enforcement of operating guidelines of septage collection to address overflow and leakages which pollutes the environment (Pasi, 2022). One hundred and ten people living in a compact residential area died in India in 2019 during septic tank and sewer cleaning after getting exposed to harmful gases. To address this, Kar *et al.* (2022) designed an air purification unit capable of sucking the air during the cleaning process to maintain a clean air in the nearby surrounding. In WHO (2018), a shared cost of investment (excavation and installation of biogas systems) and maintenance (tank emptying and cleaning) of biogas reactors utilizing latrine byproduct for a larger number of users is suggested. Thus, the setting up of a legal aspect and basic regulations are expected to enable the enforcement of sanctions and penalties to defaulters.

Developing nations where lightly enforced environmental laws are prevalent due to financial constraints, must find workable solutions to their respective environmental sanitation problems (Paramita & Koestoer, 2021). Coulibaly *et al.* (2012) presumed that biogas system implementation at home will significantly help women deviate from the use of charcoal and firewood and automatically help conserve forest trees. It will also reduce cost budgeted for other energy source like natural gas for cooking and electricity bill from town supply power outpost. In West Africa where specific quantity of FS generated is not properly documented, demand for FS management services will be difficult to predict (Odey *et al.*, 2019). Nevertheless, putting in place a scheduled pit or septage tank emptying system (Peal *et al.*, 2014) will provide researchers and potential business entrepreneurs with reliable data to make adequate use of the waste product. In addition, through empirical studies, FS accumulation rates (Blackett *et al.*, 2014) either per household, per toilets or per region per day should be determined.

CONCLUSION

Phosphorus, biogas, biofertilizer and other chemicals can be recovered from FS and be used to generate energy and produce food. In the process, dangers with poor sanitary situations in rural areas and urban slums may be fully addressed. This research could only pinpoint few cases where FS was explored to generate useful products due to limited concern given to the waste material. Findings by various researchers in Table 1 shows that under a controlled environment, high amount of biogas may be produced from FS. There is hence the need to further enlighten the populace of the benefits of channeling OWHB generated at schools, homes, markets, refugee camps, prisons, hotels and transport stations to either biogas/biofertilizer production or chemical synthesis. Though costly for a large recovery implementation scheme, further cost reduction by adopting non-conventional construction materials like precast cement, ferro-cement etc., may be recommended. Redesign of household toilets to provide for safe biogas recovery is suggested.

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